



X RME 1284





Digitized by the Internet Archive in 2023 with funding from Kahle/Austin Foundation

Electrical Machinery

240 ILLUSTRATIONS

Prepared Under Supervision of FRANCIS H. DOANE, A. M. B.

DIRECTOR, ELECTRICAL SCHOOLS, INTERNATIONAL CORRESPONDENCE SCHOOLS IN COLLABORATION WITH EDGAR KNOWLTON, Electrical Engineer AND OTHER AUTHORS

ALTERNATORS
TRANSFORMERS
ALTERNATING-CURRENT RECTIFIERS
ALTERNATING-CURRENT MOTORS AND
SYNCHRONOUS CONVERTERS
INDUSTRIAL MOTOR APPLICATIONS
STORAGE BATTERIES

Published by
INTERNATIONAL TEXTBOOK COMPANY
SCRANTON, PA.
1924

Alternators: Copyright, 1914, by International Textbook Company.

Transformers: Copyright, 1914, by International Textbook Company.

Alternating-Current Rectifiers: Copyright, 1914, by International Textbook Company.

Alternating-Current Motors and Synchronous Converters: Copyright, 1914, by International Textbook Company.

Industrial Motor Applications: Copyright, 1914, by International Textbook Company.

Storage Batteries: Copyright, 1914, by International Textbook Company.

Copyright in Great Britain

All rights reserved

Printed in U. S. A.

Press of International Textbook Company Scranton, Pa. 384

PREFACE

The volumes of the International Library of Technology are made up of Instruction Papers, or Sections, comprising the various courses of instruction for students of the International Correspondence Schools. The original manuscripts are prepared by persons thoroughly qualified both technically and by experience to write with authority, and in many cases they are regularly employed elsewhere in practical work as experts. The manuscripts are then carefully edited to make them suitable for correspondence instruction. The Instruction Papers are written clearly and in the simplest language possible, so as to make them readily understood by all students. Necessary technical expressions are clearly explained when introduced.

The great majority of our students wish to prepare themselves for advancement in their vocations or to qualify for more congenial occupations. Usually they are employed and able to devote only a few hours a day to study. Therefore every effort must be made to give them practical and accurate information in clear and concise form and to make this information include all of the essentials but none of the non-essentials. To make the text clear, illustrations are used freely. These illustrations are especially made by our own Illustrating Department in order to adapt them fully to the requirements of the text.

In the table of contents that immediately follows are given the titles of the Sections included in this volume, and under each title are listed the main topics discussed.

INTERNATIONAL TEXTBOOK COMPANY



CONTENTS

Note.—This volume is made up of a number of separate Sections, the page numbers of which usually begin with 1. To enable the reader to distinguish between the different Sections, each one is designated by a number preceded by a Section mark (§), which appears at the top of each page, opposite the page number. In this list of contents, the Section number is given following the title of the Section, and under each title appears a full synopsis of the subjects treated. This table of contents will enable the reader to find readily any topic covered.

ALTERNATORS, § 34	Pages
Types and Classes	1-6
Structural Features	7-21
Stator Cores	7-11
Laminations; Assembly.	
Stator Windings	11-21
Bar windings; Coil windings; Stator conductors and coils.	
Rotor Construction	22–2 6
Governing features; Salient-pole rotors; Rotor windings.	
Miscellaneous Parts	27-32
Collectors; Bearing; Ventilation.	
Special Structural Features	33-49
Engine-Driven Alternators	33–34
Waterwheel-Driven Alternators	35–36
Steam Turbo-Alternators	37-49
Structural features; Stator construction; Rotor construction; Miscellaneous parts of steam turbo-alternators; Ventilation.	
Connections of Alternator Windings	50-58
Armature Connections	50–58
TRANSFORMERS, § 35	
General Description	1-18
Fundamental Principles	1- 5

TRANSFORMERS—(Continued)	
` ,	Pages
Structural Features	6–18
Operation of Transformers. Cooling Transformer Insulation Application of Transformers. Characteristics of Transformers. Interconnection of Transformer Coils.	19–50 19–26 27–31 32–38 39–42 43–50
ALTERNATING-CURRENT RECTIFIERS, §	36
Voltaic Arc and Storage Battery. Rectifying Devices. Mechanical and Electromagnetic Rectifiers. Synchronous Switching Rectifiers. Electrolytic Rectifiers Description of Mercury Rectifiers. Applications of Mercury Rectifiers. Charging storage batteries; Operating arc lamps; Operating moving-picture machines.	1 2-26 3 3-7 8 9-15 16-26
ALTERNATING-CURRENT MOTORS AN SYNCHRONOUS CONVERTERS, § 37	ID
Polyphase Induction Motors	1–25 1
Polyphase Motor Primaries	2– 6 7–20
Performance and Speed Control	21-24
Induction Generators	25
Single-Phase Motors Description and classification; Split-phase motors; Shaded-pole motors; Single-phase series motor; Repulsion motors.	26–34
Synchronous Motors	35–43
Synchronous Converters	44–57

INDUSTRIAL MOTOR APPLICATIONS, § 38

	Pages
General Considerations	1-10
Choice of systems; Choice of motors; Group drive and individual drive; Load factor; Flywheels.	
Mechanical Connections	11-39
Rope drive; Chain drive; Belt drive; Spur-gear drive; Woodworking; Machine tools; Cranes and hoists; Pumps; Fans, blowers, and exhausters; Periodic service.	
STORAGE BATTERIES, § 51	
Introduction	1- 3
Lead Cell	4-36
Construction of Lead Cell	4-10
Fundamental types of plates.	
Component Parts of Lead Cell	11-16
Characteristics of Lead Cell	17-24
Capacity; Voltage; Internal resistance; Specific gravity of electrolyte; Temperature; Efficiency.	
Care and Operation of Lead Batteries	25 –36
Nickel-Iron Alkaline Cell	37-45
Construction; Characteristics of nickel-iron cell; Operation and care.	
Storage-Battery and Controlling Apparatus	46-70
Control of charge; Control of discharge; Counter-	



ALTERNATORS

TYPES AND CLASSES

- 1. Generation of Alternating Current.—When a conductor is moved across a succession of magnetic fluxes that have alternately opposite directions, or when the fluxes are made to cross the conductor, alternating electromotive force is induced in the conductor, and alternating current is established in the circuit of which the conductor forms a part. Alternating electromotive force is thus induced in the armature conductors of practically every electric generator. In a direct-current generator, the commutator converts, or rectifies, the alternating current so that the current in the external circuit is direct. An alternating-current generator, commonly called an alternator, delivers alternating current to the external circuit.
- 2. Essential Parts of Alternators.—The two main essential parts of every electric generator are, therefore, the armature, or the part that carries the conductors in which electromotive force is induced, and the field, or field magnets, in which the fluxes are established.

The field magnets of alternators are excited by direct current, which is usually generated by smaller direct-current generators called *exciters*. In large stations, several exciters may feed into one set of bus-bars from which a number of alternators receive exciting current. In rare cases, the alternator is provided with a commutator from which exciting current is taken, and the alternator is then said to be *self-exciting*.

3. Phase. -According to phase, alternators are classed as single-phase, two-phase, three-phase, and six-phase. A single-

phase alternator generates one alternating electromotive force; a two-phase, sometimes called *quarter-phase*, alternator, two alternating electromotive forces differing in phase by 90 time-degrees; a three-phase alternator, three alternating electromotive forces 120 time-degrees apart; and a six-phase alternator, six electromotive forces 60 time-degrees apart. The term *poly-phase* is a general designation applied to alternators and circuits of more than one phase.

Some two-phase machines are in use, but by far the greater

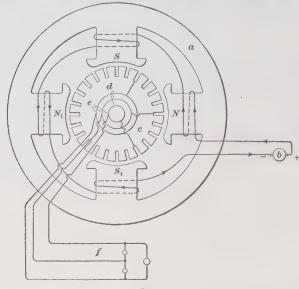


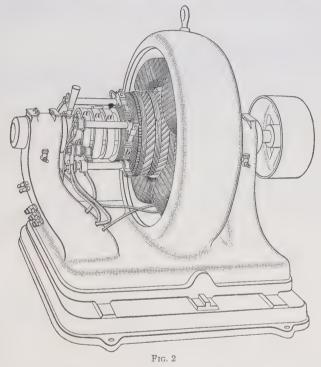
Fig. 1

number of alternators are three-phase machines. Single-phase current is much used, but it is generally taken from individual phases of polyphase machines.

4. Revolving-Armature Alternators.—According to the arrangement of essential parts, alternators are classed as revolving-armature machines and revolving-field machines. Fig. 1 shows diagrammatically a three-phase revolving-armature alternator. The stationary member consists of a frame a supporting magnet poles N, S, N_1 , and S_1 . These poles are

excited by current from a small direct-current generator b. The current produced in the winding of the armature c is carried through collector rings d and brushes e to the external circuit f.

Revolving-armature alternators are now so little used that only a general reference to them will be made. Fig. 2 shows a small self-excited machine of this class for use in small, isolated

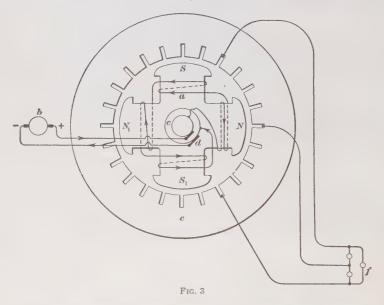


plants. The three collector rings for the three phases are shown at a, and between them and the end of the armature winding is the commutator b for rectifying the exciting current, all of which is supplied by a separate winding on the armature. The brushes are mounted on a rocker-arm so that they can be rotated to a position of sparkless commutation of the exciting current. Such generators are not built in large sizes nor for high voltages, because of the difficulties encountered in

insulating the windings and collectors, as well as the danger resulting from exposed collectors.

5. Revolving-Field Alternators.—The demand for greater capacities and voltages is met by the revolving-field alternator, in which only the exciting current is transmitted to the rotating element, or rotor, at relatively low voltage. The revolving-field alternator has almost entirely superseded the earlier type of revolving-armature machines.

Fig. 3 shows a diagram of a three-phase revolving field alternator. The field a has four poles N, S, N_1 , and S_1 . The



windings on these poles are connected to the exciter b, through collector rings c and brushes d. The stationary armature e is provided with slots on the inner periphery to receive the winding in which the electromotive force is generated. The terminals of the winding are connected to the external circuit f.

6. Method of Rating Alternators.—The most common method of rating alternators in the United States is in *kilovolt-amperes*, which is abbreviated k. v. a., read by pronouncing the

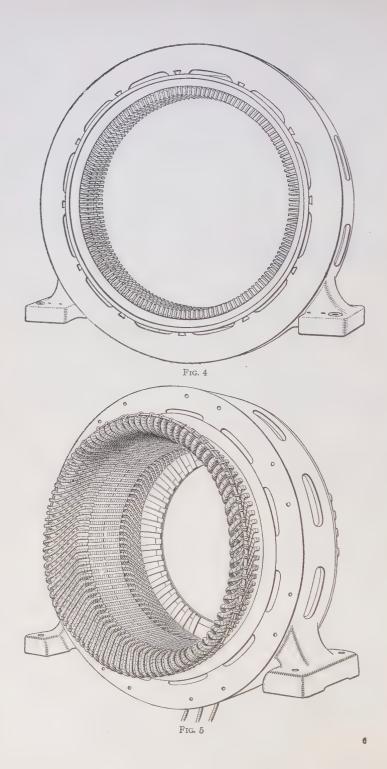
letters k v a separately. One kilovolt is 1,000 volts. If I is the current per terminal and E the volts between terminals, the kilovolt-amperes for a single-phase circuit is $\frac{IE}{1,000}$; for a two-

phase circuit, $\frac{2IE}{1,000}$; and for a three-phase circuit, $\frac{\sqrt{3}IE}{1,000}$. The

rating in kilovolt-amperes means the same as the rating in kilowatts at unity power factor. If an alternator is rated in kilovolt-amperes, its output in kilowatts is equal to the product of the kilovolt-ampere rating and the power factor at which it is operated; thus, a 10,000 kilovolt-ampere alternator will deliver 9,000 kilowatts at a power factor of 90 per cent.; 8,000 kilowatts at a power factor of 80 per cent.; and so on. The rating in kilowatts is sometimes specified, but it is indefinite unless accompanied by the statement of the power factor.

7. Methods of Driving Alternators.—Alternators may also be classed as belt or rope driven, steam-engine driven, gas-and oil-engine driven, water-wheel driven, and steam-turbine driven. Each of these classes has some special features of construction, on account of the speed and characteristics of its driver, but the essential features are the same for all.

A belt-driven alternator is usually purchased complete with bearings, shaft, and pulley ready to receive the driving belt. There is also generally provided a sliding base and a screw device for adjusting the belt tension. The rotating element of an engine-driven alternator is generally pressed on an extension of the engine shaft, and the engine and alternator form a compact unit. Alternators driven by waterwheels and steam turbines are usually coupled to the driving shaft. The name turbo-alternators is sometimes applied to turbine-driven alternators, and the prefix steam or water indicates the kind of turbine.



STRUCTURAL FEATURES

STATOR CORES

GENERAL APPEARANCE

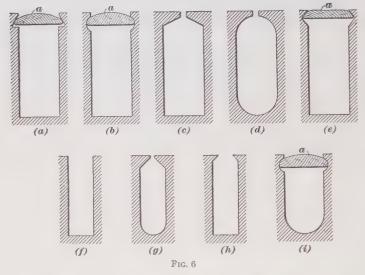
8. The stator, or stationary part, constituting the armature of a revolving field alternator consists essentially of a laminated iron core and its supporting structure; the core is located inside the structure and carries the stator windings in slots in its inner cylindrical surface. Fig. 4 shows the assembly of a core in a supporting frame, and Fig. 5, a complete stator with the windings in place. When the rotor is in place and the machine complete, guard rings, or brackets, one of which can be seen on the rear of the stator, extend over the projecting windings and protect them. Alternator stators differ in details of design, according to size and to differing judgments and tastes of designers, but the general appearance is as shown.

LAMINATIONS

- 9. Material.—The stator laminations are punched from large sheets of soft iron selected for low hysteresis loss. Stator cores are laminated for the same reason as those in the armatures of direct-current machines, namely, to reduce eddy currents. The sheets are thin in order to keep the eddy-current loss as low as possible, because these currents vary as the square of the thickness of the laminations; .014-inch laminations are in general use.
- 10. Methods of Punching.—Laminations with outer diameters not exceeding 12 inches are generally punched in one piece; those of larger outer diameter are punched in segments, as will be shown later. The number of segments to form a circle is chosen with reference to the number of slots, preferably

so that dividing lines between segments come at slot centers; if the teeth are very wide, the divisions can well be made at tooth centers.

11. Stator Slots.—Open stator slots, such as those shown in Fig. 6 (a), (b), (e), (f), and (i), are generally used in American made alternators. The forms shown in (a), (b), and (e) are most commonly used. The coils are held in place in open slots by wooden or fiber wedges a in dovetails near the top of the teeth.

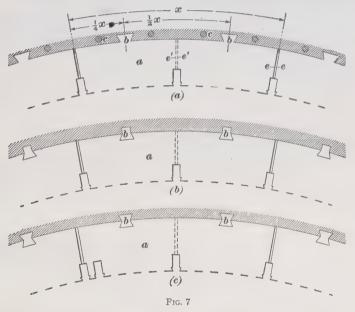


With open slots, the coils can be completely formed and insulated before being placed in the slots, thus generally permitting better workmanship and lower cost than is feasible with the semiclosed slots shown in (c), (d), (g), and (h). In the latter, the windings must be fed through the narrow openings between tooth tips. This advantage of open slots may become especially important to the operator in case repairs are essential. Semiclosed slots have some advantages from a design standpoint and they can be used with little difficulty when the slot conductors consist of single bars that can be thrust endwise through them.

12. Annealing and Insulating.—The action of the die in punching the laminations hardens them. Therefore, to remove this hardness so as to minimize hysteresis loss, the sheets are annealed before assembling the cores. Insulation is essential between laminations to prevent eddy currents. This insulation may be very thin; a layer of enamel or japan baked on is sufficient.

ASSEMBLY

13. One-piece stator-core punchings are usually assembled inside supporting ribs in the frame, being keyed or dove-



tailed to them to prevent turning. Clamping rings that are pressed against the ends of the core and then keyed prevent axial movement.

14. Segmental punchings are assembled in several ways. Some of the most common methods are shown in the sectional views, Fig. 7, in which only enough slots are indicated on each segment to show the dividing lines between segments.

In the method shown in view (a), each segment a is held in place by two dovetail projections b that fit into corresponding slots milled in the cast-iron supporting frame. The laminations are clamped between end plates secured by bolts c. The ends of the punchings are cut a little less than the full arc x, giving a small clearance e e between abutting ends and thus making the laminations go into place more easily. The next layer of laminations is put on so that the joints come midway between the joints of the first layer, as shown at e' e'; thus, the joints of no two adjacent layers are in line with each other. Other kinds of dovetail supports are shown in views (b) and (c). The dovetail pieces b are fastened to the frame, and notches are punched in the laminations, thereby requiring less iron than if the sheet were large enough to make the dovetail a part of the lamination.

Since the core slots must be smooth and perfectly alined, the ends of long steel keys the exact size of the slots are usually driven into a few slots after several laminations are in place, and the remaining laminations are assembled on these keys.

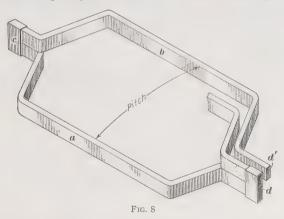
- 15. Air Ducts.—At intervals in the core are ducts for the passage of air that cools the armature. These ducts are formed by means of suitable spacers, or spacing strips. Enough spacing strips must be used to support each tooth securely—two per tooth for wide teeth.
- 16. Clamping.—In order to prevent vibration of the teeth under the rapidly changing magnetism, they are well braced not only in the air ducts, but also at the ends. Spacing strips, or end fingers, are used between the core and the end flange, a finger bracing each tooth. Sometimes the fingers are cast integral with the end flange, especially when the flange is cast in segments. The core is firmly pressed together, and the flanges are keyed or otherwise fastened. Cores more than 16 inches long are usually pressed every 10 or 12 inches during assembly; this practice is very common with vertical cores. The final pressure is very heavy, sometimes several hundred tons for long cores. The flanges are secured between a shoulder on one end of the stator spider and keys on the other end.

17. Preparation of Slots.—The slots should be smooth so as to prevent the insulation on the conductors from being cut. The method of assembling described insures fairly smooth slots, but each slot is finished either by slightly filing it or by driving through it a broach, that is, a piece of steel having the sides fluted to form cutting edges. At the ends, the slot corners are filed smooth and round to avoid cutting the insulation where the coils are bent around the corners. No more filing or broaching should be done than is absolutely necessary, since it burrs the metal so as to form paths for eddy currents close to the insulation on the conductors, where the heating caused by these currents will be most detrimental.

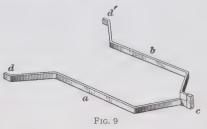
STATOR WINDINGS

BAR WINDINGS

18. Stator windings are of two general types, based on the form of conductor used, namely, bar windings and coil windings. If the capacity of the machine is such as to permit the



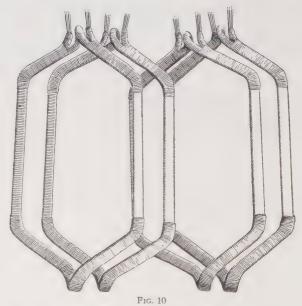
use of very few conductors per slot, they are usually in the form of insulated bars. All bar windings are in two layers; that is, two insulated bars are laid, one over the other, in each slot or four bars are laid in two pair, one pair over the other. Bar windings may be considered in two classes, according to the



form of the end connections of the bars, as *lap* and *wave* windings.

19. The lap winding is the most common form of bar winding. The bars, as shown in Fig. 8, are so shaped that they can be

connected in pairs forming loops, of which one side a fits in the bottom of a slot and the other side b fits the top of another slot at the proper distance, or pitch, from the first. The ends of bars forming a loop are joined, one over the other, by a clip c securely soldered in place; the other ends d and d' are joined with corresponding ends of other coils. The fact that



these front-end connections d or d' approach each other so that the circuit of which the coil forms a part overlaps itself,

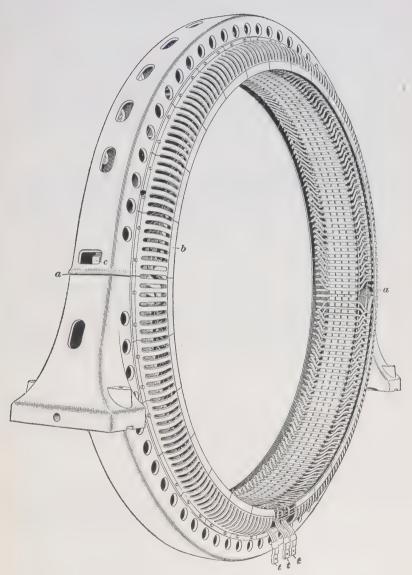


Fig. 11

as on a parallel wound direct-current armature, gives this winding its name.

20. Bars forming a loop, or turn, for a **bar wave winding** are shown in Fig. 9. They differ from those of the lap-wound coil in that the ends d and d' are separated, as on a series-wound direct-current armature. The letters abc have the same signification here as in Fig. 8.

COIL WINDINGS

21. Two-Layer Winding.—If many conductors are used per slot, they are arranged in coils, which may be of either the two-layer or the one-layer type. Four coils of the two-layer

type are shown in Fig. 10. The only essential difference between these coils and the loop shown in Fig. 8 lies in the number of turns per coil. Fig. 11 shows a stator wound with two-layer coils. This stator is in two parts, divisible at planes a, where the omission of a few coils is indicated; these coils are installed in the completed stator. The venti-

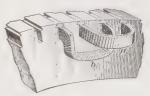


Fig. 12

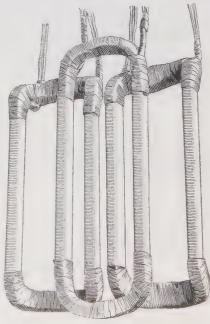


Fig. 13

lated end shields are shown at b, and the head of a bolt for holding the two parts of the frame together is shown at c. The terminals of the stator winding are shown at t.

22. One-Layer Chain Winding.—One-layer coil windings are of the *chain type* and the *basket type*. Fig. 12 shows two coils of the chain type; each side of a coil fills a slot, and the ends of the coils interlink, as shown at a and b. Fig. 13 shows a set of three coils for a three-phase chain winding with

three slots per pole, one slot per phase per pole, and Fig. 14 shows the appearance of such coils assembled on the stator core, the coil interconnections showing at a. Fig. 15 illustrates coils for a three-phase chain Phase 3 winding with two slots per pole per phase. The part of the insulated coil that is to lie in the slots is usually molded under pressure and is encased in leatheroid, which serves as mechanical protection against injury when placing the coils in the slots.

23. Fig. 16 illustrates different kinds of single-layer chain windings used on alternator stators with

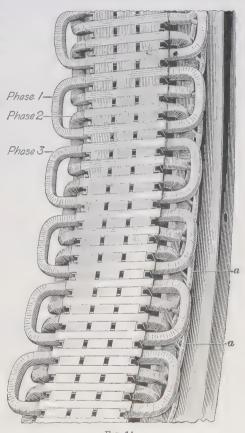


Fig. 14

three, four, and six slots per pole. The coils of each phase are shown in distinctive color, and the method of drawing them indicates how they are interlinked at the ends. The spacing is indicated in electrical degrees, the space between centers of two successive north poles being 360 electrical degrees. Empty

slots may occur when punchings for polyphase machines are used for the cores of single-phase machines, as shown in (a) and (f); omitting either phase in (c) would give a single-phase winding with two empty slots per pole.

24. One-Layer Basket Winding.—The basket winding shown in Fig. 17 consists of coils of uniform shape that cross one another at the ends. This winding is little used on alternators, its use being confined mostly to small alternating-current motors.

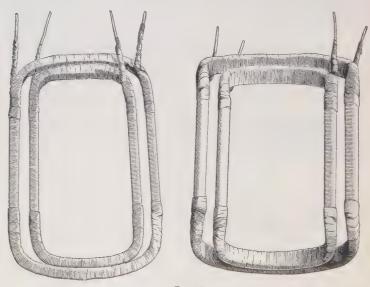
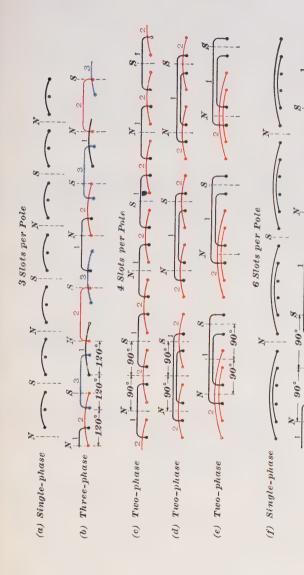


Fig. 15

25. One-layer windings have the advantage of more economical use of slot space than two-layer windings. One-layer chain windings also have the advantage of greater separations of coil ends outside the slots, but they have the disadvantage of requiring several different forms of coils for a machine. The basket winding obviates this disadvantage, but, in turn, it has the disadvantage of massing, or crossing, at the ends, thus making good insulation and ventilation more difficult.



264B-IL T 134 §34

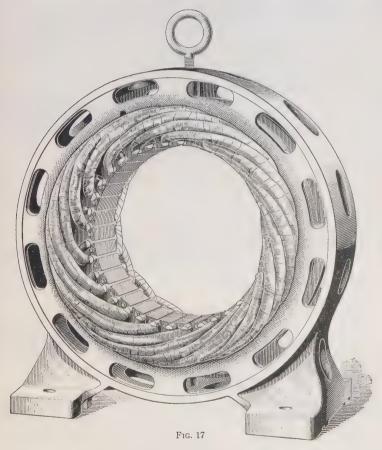
(h) Three-phase

(g) Two-phase

Frg. 16



26. One-Layer Slot, Two-Layer End Winding.—A type of winding unit having one layer in the slot and two layers at the ends is shown in Fig. 18. One side of the coils projects a short distance straight from the slots, as at a; then it turns and continues to a point b, where a compound turn



or twist, is made to pass under the ends of neighboring coils, as at c; and, finally, it turns upwards and into the plane of the slots at d. The other ends of the coils are duplicates of the ends shown, except that conductor ends are brought out for connections. This winding utilizes slot space economically

ILT 384-3

and requires but one form of coils. The complicated bends, however, are hard to make, especially with heavy copper, and

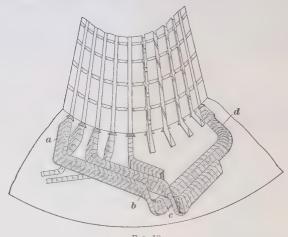


Fig. 18

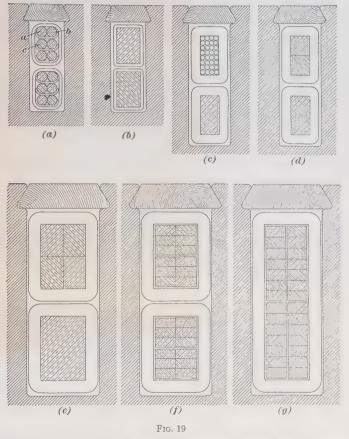
the insulation and ventilation of the coil ends are not so easy as with chain windings.

STATOR CONDUCTORS AND COILS

27. Conductors.—Fig. 19 shows cross-sections of alternator slots with different forms of conductors. Round wire, as in (a), is used for small coils of many turns, although it does not fill the slot space so economically as square wire. However, square wire gives so much trouble by twisting at the bends in the coils that it is seldom used.

Flux crossing the slots between teeth is most dense near the air gap, thus causing slightly higher voltage in the part of a solid conductor near the top of a slot than in the part near the bottom. To prevent useless eddy currents from this cause, sectional, or stranded, conductors are generally used when large current capacity is needed. In some cases, such conductors are employed only in the tops of the slots, where eddy currents would be strongest, as in (c), (d), and (e); in other cases both the top and the bottom conductor are composed of strands, as in (f) and (g)

Fig. 19 (b), (c), (d), and (e) show sections of bar windings in which the coils are formed in halves and connected after placing them in the slots. This method permits the use of different conductor sections in the top and the bottom of the slot. In (c), the upper conductor is a cable pressed into a rectangular



cross-section; in (d) it is divided crosswise with a thin layer of insulation in the division; and in (e) it consists of four strands of rectangular copper. Views (a) and (f) show two-layer coil windings, the former with round wire and the latter with rectangular wire, and (g) shows a single-layer coil winding with

rectangular wire $\,$ In both (f) and (g), the coils are sectionalized by cross-divisions of insulation that is thick enough to prevent eddy currents.

- 28. Coil Formation.—Accurately made forms are required to shape the coils. Some of these coil forms are comparatively simple wooden structures; others are of metal and sometimes very complicated and expensive. The construction of coil forms to shape coils only for repairing machines is seldom good economy, provided complete coils can be purchased of the alternator manufacturer.
- 29. Insulation of Conductors.—Sectionalizing conductors to prevent eddy currents can usually be done with very thin insulation. For example, oxidation on the copper wire is enough in the pressed cable shown in Fig. 19 (c); .005-inch paper serves in conductors shown in (d) and (e), and single cotton for the rectangular wire shown in (f) and (g).

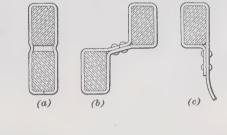
The insulation between turns of a coil must be proportional to the voltage between adjacent conductors in the coil. For example, if each turn of the coil shown in Fig. 19 (a) generates 10 volts, this voltage exists between successive turns a and b; but between turn a and the third turn c in the series, that is, between layers, the voltage is 20. Each turn is therefore wrapped with some insulating material, such as cotton cloth impregnated with varnish, and \mathbf{U} -shaped pieces of paper or fiber are placed between layers. In coils with higher voltages per turn, the conductors may be insulated with varnished cambric or mica tape, the latter consisting of thin layers of mica cemented to thin paper, the whole being about .005 inch thick. Mica tape is protected from mechanical injury by an outer wrapping of cloth tape.

30. Insulation of Coils.—The manner in which coils are insulated depends on their formation and on the voltage of the machine. The *impregnation process* is much used for coils of several turns. The formed coils are wound with a temporary covering of tape and then placed in a tank in which the temperature is raised to a high degree and from which the air is

exhausted. The heat and the vacuum combined remove every trace of moisture and practically all the air from the insulation. After this, hot insulation compound is forced in under pressure. The compound thus enters all the crevices between conductors, as well as the pores in the insulation. When the coils are removed the compound solidifies, and the coil remains a solid mass at all operating temperatures. The compound not only helps to insulate, but also readily conducts heat from the interior of the coil to the exterior. The temporary taping is removed from impregnated coils after they have cooled, and permanent

wrappings are substituted, covering all except the ends for connections.

Bar windings are insulated similarly to coils, but they are not impregnated. The materials used in insulating bars, and the number of wrappings, depend on the voltage. For low voltage, varnished or oiled cloth tape is sufficient; for high voltage, mica





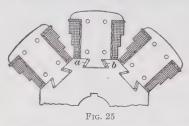
tape covered with cloth tape may be employed. The parts of the coils or bars in the slots are usually covered with an armor of tough material to prevent mechanical injury.

31. Assembly.—Properly formed coils fit very closely in the slots; in fact, some force must be used to press them into place. The ends of bars are then joined by clips as shown in Fig. 20. The clip shown in (a) is for bars that are in the same axial plane as at c, Fig. 8; that in (b), for ends in slightly different planes; and that in (c), for leads to the connection board. The clip shown in (d) is called a *pole connector*, as is explained later. All clips are well insulated with tape, shellac, etc.

for still higher speeds, as in steam-turbine alternators, very special rotor construction is essential. Such construction is described in connection with steam-turbine alternators.

SALIENT-POLE ROTORS

34. Dovetail Construction.—Rotors such as those shown in Fig. 21, in which the poles are separated from each other

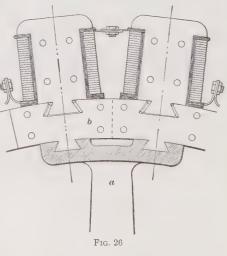


by intervening air spaces or by some non-magnetic material, are called *salient-pole rotors*. The poles are made of laminations assembled and riveted between end plates, as shown in Figs. 22 and 23. At a, Fig. 22, are shown the

laminations; at b, the end plates; at c, the rivets; and at d, the dovetail that fits into a groove in the spider rim and is held by steel wedges a, Fig. 23. The field coil fills the space formed by the overhanging pole and the flanged end plate b

above and the clamping ring c below; this ring is bolted to the spider. The laminated structure is to prevent in the structure itself eddy currents due to changes of magnetic density as the poles pass the stator teeth.

35. Bolted Construction.—Fig. 24 shows the method of bolting poles to the spider rim. An opening is punched in each lami-



nation, and these openings form in the pole a space into which a bar a is inserted. Stud bolts b through the spider rim

are screwed into tapped holes in this bar, and they are held secure by lock washers c. The contact surface d between the pole and the rim is not so large as with dovetail construction, but the difference in the reluctances of the magnetic circuits is not appreciable if the machine work is well done. Bolted construction is not generally good magnetically with cast-iron

rims, nor is it considered so strong mechanically as dovetail construction.

36. Laminated Spiders and Rims.—Fig. 25 shows the construction of a small rotor in which laminated poles are dovetailed into a laminated spider assembled on the shaft. Shims a form a surface against which to wedge the dovetail when the keys b are driven home. The coils are tapered because of the narrow space available near the spider. Fig. 26 shows the construction employed

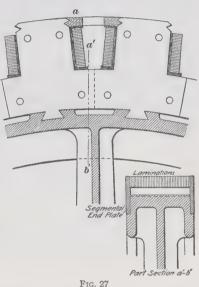
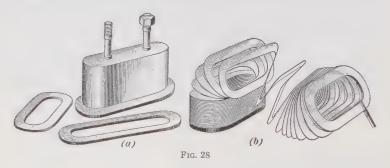


FIG. 21

for high-speed rotors, in which the spider arms a carry a laminated rim b riveted between end plates. Fig. 27 shows a section of a rim and the poles of continuous laminations. The coils are held in place by pieces a of cast copper or brass; these pieces act also as dampers to prevent sudden variations of speed when the alternator runs in parallel with others. A laminated rim with staggered joints is much stronger than one of cast iron or cast steel.

ROTOR WINDINGS

37. Coil Construction.—Rotor fields are usually excited by direct current from a 125- or a 250-volt circuit. Round wire is employed for the coils when the exciting current is small, and flat copper strip wound on edge, as in Fig. 28, for larger current. The latter construction is better mechanically, and, besides, it dissipates heat from the interior more readily; hence, it is employed wherever the current is large enough to justify its use. Fig. 28 (a) shows a pole piece, a short-circuiting collar, and an insulating collar, and (b), a strip-wound coil pulled apart to show the construction. The short-circuiting collar is placed on the pole next to the flange, in which position



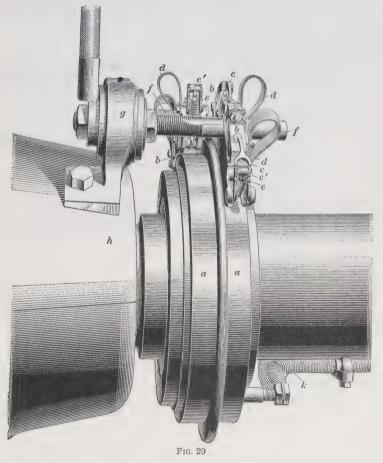
it serves to steady the flux in the pole. Next to this collar comes the insulating collar, then the coil, which is insulated and cemented together, and lastly another insulating collar next to the rim of the spider.

38. Assembly.—The field voltage is so low that a high degree of insulation is not needed, but the heavy mechanical stresses require very secure assembly to prevent any movement of the coil. Figs. 23 to 27, inclusive, show coils in place, and Fig. 26 shows connections between coils. All the coils are wound alike, and the correct polarity is obtained by making the interconnections alternately at the top and the bottom. On high-speed rotors, these connections must be supported by insulated clamps.

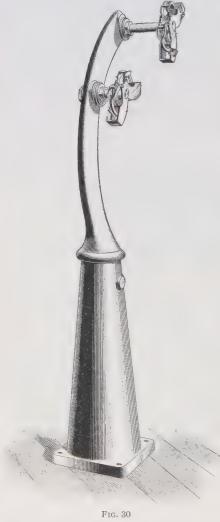
MISCELLANEOUS PARTS

COLLECTORS

39. The collector on a revolving-field alternator carries the exciting current from the stationary to the rotating part of



the circuit. It consists essentially of two collector rings sliding under stationary brushes. The complete collector includes all the means for supporting and holding the rings, brushes, and connections. It may take any one of several forms.



One form of collector is illustrated in Fig. 29. The rings are shown at a, and at b are shown the brushes, which are held on the rings by fingers c and springs e. The pull of the springs can be adjusted by placing their supporting casting c' in different notches in the forks of the fingers. Wovenwire cables, or pigtails, d furnish low-resistance current paths between the holders and brushes. The brush holders are carried on studs f supported by castings g mounted on the bearing housing h. The connections leading from the collector rings to the field coils are well insulated, wrapped with cord, as at k, and securely fastened to the shaft.

Large alternators, especially those for direct connection to engines, usually have brush holders supported on pedes-

tals or on brackets attached to the stator frame. Fig. 30 shows one form of pedestal for this purpose; the connections to the brush-holder study are carried up through the interior of the pedestal.

40. Rings.—The collector rings are usually made of cast iron; they are mounted on a shell, or spider, one form of which is shown in Fig. 31. In this case, both the rings and the spider

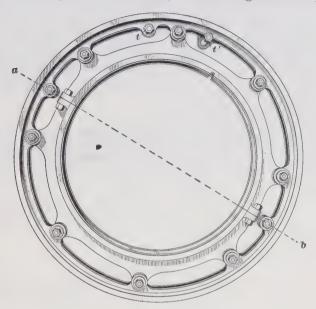
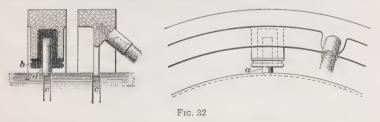


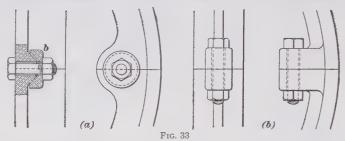
Fig. 31

are split on the line ab to facilitate ready removal without dismantling the machine. Split rings are unnecessary on small machines that may be easily dismantled. Fig. 32 shows a method of supporting the rings on pins a encased in molded



insulation b and fitted into holes in the bottom of grooves c in the shaft. These holes prevent the ring from turning on the shaft.

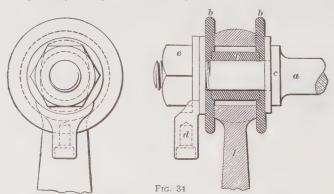
Fig. 33 shows two methods of clamping split rings. In view (a), a conical washer b is clamped against a conical seat, half



of which is part of each half of the ring; in (b), use is made of bolts that pass through lugs on the ring segments.

41. Brush Holders and Brushes.—Brush holders are made in endless variety. In most cases, each brush holder consists essentially of a stationary box in which a brush slides freely and a spring-actuated device for holding the brush against the ring.

Brushes made of carbon or of graphite, or of a mixture of the two materials, are most frequently used. They work well on rings of any material, especially on cast-iron rings, which take a high polish. Brushes made of other materials, such as mixtures of carbon or graphite with copper dust, are sometimes used, especially if high conductivity is desirable.

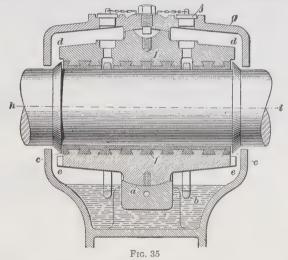


42. Brush-Holder Support.—Fig. 34 shows a method of supporting the stud a on which the brush holders are clamped.

The arm f has a slotted opening in which the stud is clamped and in which its position can be adjusted to bring the brushes nearer to the rings or farther from them. The stud is insulated from the arm by a sleeve l and washers b placed between metal washers. One of these metal washers rests against a shoulder c on the stud, and the other serves as a base for the washer part of terminal d, outside of which is a clamping nut e. The arm f corresponds to the arm g, Fig. 29.

BEARINGS

43. Alternator bearings are practically always self-alining and self-oiling, the usual construction being as shown in Fig. 35. The bearing rests on a spherical surface a, permitting it to aline itself perfectly with the direction of the



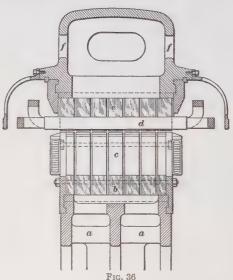
shaft. Oil rings b hang in slots in the upper half of the bearing and dip into oil in the reservoir below; these rings, resting on the shaft, turn with it and carry oil to the top of the shaft, whence it is distributed through grooves in the bearing surface.

The collars c on the shaft limit the end movement and prevent oil from escaping along the shaft. The lips d on the bearing catch the oil thrown from the collar and deliver it to

the oil chamber below, a section of each lip being cut away at e for this purpose. The Babbitt lining f is held in the shell by dovetails. The top part of the bearing housing g can be removed, the joint of the two parts being along the horizontal plane h i. The oil rings can be inspected through the sight holes j.

VENTILATION

44. Air circulation for ventilating the cores and windings, where heat is occasioned when the machine is operating, is provided by the fanning action of the rotor and its ventilating vanes, which action causes air to pass through the various



openings and airducts. Fig. 36 shows a crosssectional view made in a plane that includes the center of an alternator shaft. This alternator has a laminated field rim, such as is shown in Fig. 27. permitting air ducts through the field rim and poles to match those in the stator core. When the field rim is solid, holes are made in it for the passage of air.

When the alterna-

tor, Fig. 36, is operating, air passes from the center out through openings in the spider rim and between the arms at a, through ducts in the laminated rim b and the pole piece c, past the stator windings d, through the ducts in the stator core e into the frame, and out through the numerous openings f.

Short machines do not require holes or ducts in the field rim, because they receive enough air through the spaces between the poles, as at a', Fig. 27.

SPECIAL STRUCTURAL FEATURES

ENGINE-DRIVEN ALTERNATORS

45. By special structural features is here meant those necessary to fit an alternator for a particular service or a particular method of drive. The general construction already described

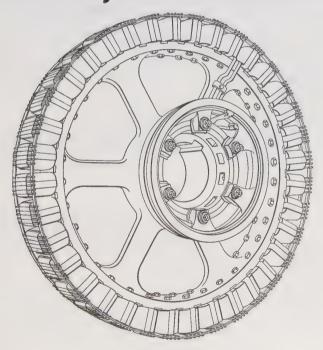


Fig. 37

applies to some features of the following machines, and only those features differing from preceding descriptions will be considered. 46. Alternators direct-driven by reciprocating steam engines and gas or oil engines are usually of large diameter and short length. When operated in parallel with other alternators, measures must be taken to eliminate slight inequalities of peripheral speed that otherwise occur with reciprocating-engine drive. Such measures usually consist of heavy flywheels, either separate from the rotor, but on the same shaft, or as a part of the rotor construction, in what are known as flywheel alternators.

For gas- or oil-engine drive, where the peripheral speed is less uniform than with steam engines, the flywheel is made heavier, and in some cases a special *squirrel-cage winding* is placed over

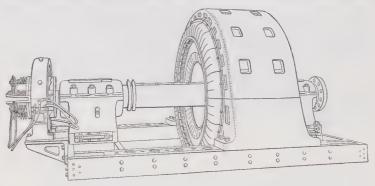


Fig. 38

the pole faces, as in Fig. 37. This winding serves to hold the speed constant. The action of a squirrel-cage winding is treated in a later Section.

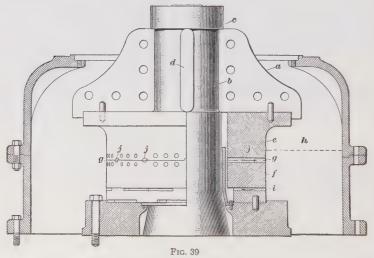
47. Flywheel Alternators.—The distinguishing feature of flywheel alternators is the heavy construction of the spider rim, which construction gives the rotor the necessary inertia, or flywheel effect. The large diameter and the resulting high stresses necessitate secure attachment of poles, as in Figs. 26 and 27, and also heavy frame construction to obtain rigidity. The stator frames of large engine-type alternators are usually shipped in sections, and provisions are made for securing the joints, as in Fig. 11.

- 48. Ventilation.—Engine-type alternators are usually cool in operation because of the large surface per unit loss and because of ample air movement. The only difficulties met with are the discharge of heated air into the pit in which the lower part of the frame hangs and the reentrance of this air to the machine. These difficulties, when serious, are overcome by omitting the openings in the part of the stator frame below the floor level so that heated air is discharged only above the floor.
- 49. Facilities for Repairs.—The engine and the alternator are assembled as a unit, the bedplate, the bearings, and the shaft being supplied by the engine builder; also, the alternator is usually arranged so that the windings can be made accessible for repair without taking the engine to pieces. A very good method is to provide for sliding the complete stator axially until it is clear of the rotor, as is explained later in connection with Fig. 38; another method is to provide for raising the upper half of the stator, but this necessitates the removal of a few stator coils at each joint, as in Fig. 11.

WATERWHEEL-DRIVEN ALTERNATORS

- 50. The speed of waterwheels depends on the pressure of the water. Alternators for waterwheel drive are therefore designed for speeds ranging from that of reciprocating engines to that of slow-speed steam turbines. The construction for all speeds must be very substantial to resist mechanical stresses that accompany a sudden removal of the load. The waterwheel governors, however, check the flow of the water to the turbines before there is much change in the speed of the alternators. Two types of waterwheel-driven alternators are in use, horizontal-shaft machines and vertical-shaft machines.
- 51. Horizontal-shaft alternators for waterwheel drive resemble very closely the engine-driven machine, but they are supplied complete with bedplate and pillow-block bearings, as shown in Fig. 38. This illustration shows a direct-connected exciter at one end and space for sliding the stator toward the exciter to gain access to the windings.

- 52. Vertical-shaft waterwheel alternators are distinguished chiefly by the bearing construction. Guide bearings maintain the rotor in a vertical position, and a thrust bearing in connection with the alternator or the waterwheel supports the weight of the revolving parts of both. The guide bearings, which take only the side pressure, are less substantial in construction than the bearings of a horizontal machine of the same weight; besides, they require a different method of lubrication. Provision is made by pumping, by elevated oil reservoirs, or otherwise to force the oil into the vertical bearings.
- 53. Thrust Bearings.—Thrust bearings are of two types, namely, disk bearings and roller bearings.



54. In the disk bearing, shown in Fig. 39, a collar a, in halves, is bolted around the shaft b immediately under the shaft collar c and is driven by a key d. Below this rotating collar is the rotating part e of the bearing, it being separated from the stationary part f by the bearing surface g. Oil stands in the chamber at the level h and enters openings i in the stationary part; when the shaft is rotating, centrifugal force causes circulation of the oil out through radial openings f between the bearing surfaces, as indicated by the arrows.

The roller bearing is practically the same in construction as the disk bearing, with the addition of rollers between the moving and stationary parts.

55. Ventilation.—Large horizontal-shaft alternators of the waterwheel type are often supplied with fans to insure uniform temperatures throughout the machines. This is especially true when the speed is so high that braces are necessary between the rotating poles. Such braces interfere with air circulation, sometimes necessitating fans at the ends of the rotor.

Vertical-shaft alternators may be ventilated from either end or from both ends. The openings in the top are relatively small and must be covered with gratings to prevent the entrance of coarse articles, such as tools. The more desirable method is to introduce air from below, preferably taking it from outside the building when weather conditions permit. The use of fans and guide vanes is generally necessary to direct the air in the proper paths.

STEAM TURBO-ALTERNATORS

STRUCTURAL FEATURES

56. The chief distinguishing structural features of steam-turbine-driven alternators are their small dimensions, as com-

TABLE I
COMPARATIVE FEATURES OF ALTERNATORS

Feature	Engine- Driven	Water- wheel Driven	Steam- Turbine Driven
Capacity, kilovolt-amperes Revolutions per minute Diameter at armature face, inches Length of armature core, inches Peripheral speed, feet per minute. Ratio of diameter to length of core	1,500 100 180 12 4,700	1,500 360 72 20 6,700 3.6	1,500 1,800 28 26 12,700 1.08

pared with other alternators of equivalent capacity, and the rotor construction. In order to avoid excessive peripheral speed with the high rotative speeds of steam turbines, these alternator rotors are comparatively long and of small diameter. Even with these dimensions, the peripheral speeds are much higher than in other alternators, necessitating very special rotor construction.

The comparative features of engine-, waterwheel-, and steam-turbine-driven alternators are indicated in Table I.

STATOR CONSTRUCTION

57. Cores.—The stator cores of steam-turbine-driven alternators are constructed essentially the same as those of other alternators, except that, on account of the excessive

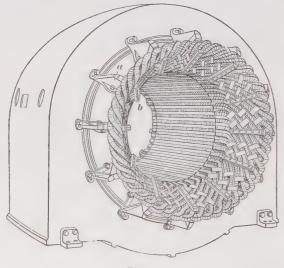


Fig. 40

length, special precautions must be taken to insure a tight core. For this reason, the frame and the flanges are much more massive than those of other types of alternators of similar diameter.

- **58.** Windings.—The conductors for such stators are bars, pressed cables, or groups of rectangular strands, as shown in Fig. 19, slots (b) to (g), inclusive. Slot (b) shows general practice with small turbo-alternators, and the other slots, in order, represent the practice with increasing sizes up to slot (g) for the largest. The stator conductors in very large alternators must be of large cross-section, and they usually consist of rectangular strands, from 20 to 40 such strands, as shown in slot (g), being sometimes employed.
- 59. If a short circuit occurs, the current, during the first half cycle, may be from 10 to 30 times normal value. decreasing in approximately 2 seconds to the established current of from 1.5 to 3 times normal current. This established current lasts as long as the short circuit and the field excitation are continued. The excessive transient overload causes heavy stresses tending to pull the coils out of shape, and secure bracing is therefore necessary. Fig. 40 shows one method of securing the coils; in addition to wedges in the slot portions, the coil ends are clamped between braces a, bolted to the frame and strips b, the clamping bolts passing through ventilating spaces in the windings. Another method is to lash the coil ends to a heavy insulated metal ring encircling them, this ring being fastened to the ends of braces like those shown at a; in this case, the strips b are omitted, and wooden blocks are secured between the coil ends to prevent sidewise movement.

ROTOR CONSTRUCTION

- 60. The most distinctive feature of steam turbo-alternators is the rotating-field structure. Several methods of construction are in use, all of which may be considered in two general classes, namely, laminated-body rotors and solid-body rotors. For large capacities at high speeds, the tendency to vibration becomes so great that the rotor shaft and body must be made solid in order to secure the requisite strength.
- 61. Laminated Rotors.—Fig. 41 shows a laminated field in process of construction. The core a, with ventilating

ducts b and dovetail grooves c, is assembled on a cast-steel spider, and the poles are made of laminated blocks d, e, and f dovetailed and wedged in the grooves c. Blocks adjacent to the field coils, such as d and e, are shaped to form slots; in this field, when completed, other rows of blocks and two additional field coils are placed outside those shown, making four coils per pole. The rivet heads on the blocks meet in the air ducts, thus maintaining the proper spacing. In some cases,

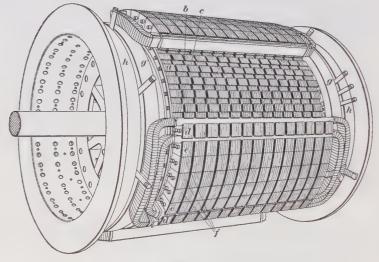


Fig. 41

the core a is made of solid steel plates of a thickness to form one of the sections between ventilating ducts.

The ends of the two inner field coils rest on retaining rings g, and the ends of the two outer coils (not shown), on rings h. The bolts projecting between the retaining rings are some of those serving to clamp plates over the coil ends, giving the finished appearance shown in Fig. 42, in which a indicates a clamping plate and b holes therein for ventilation.

62. Solid-Body Rotor With Radial Slots.—Fig. 43 shows a partly finished radial-slot rotor body and shaft machined from a solid steel forging. Large axial grooves are

still to be milled in the enlarged parts of the shaft next the rotor body for ventilating the ends of the field coils.

The complete rotor appears as in Fig. 44. The field coils are held in the slots by brass or steel wedges a driven into dovetail grooves near the tooth tips. Perforated seamless nickel-steel rings b are heated and forced over supports with a close fit; when the rings cool, they shrink against the supports with a stress somewhat greater than the centrifugal force when in operation, thus preventing looseness. These rings cover and protect

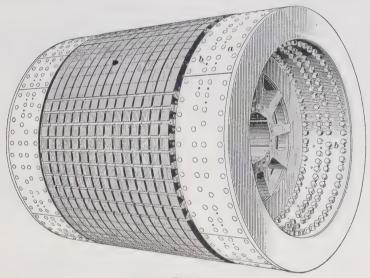
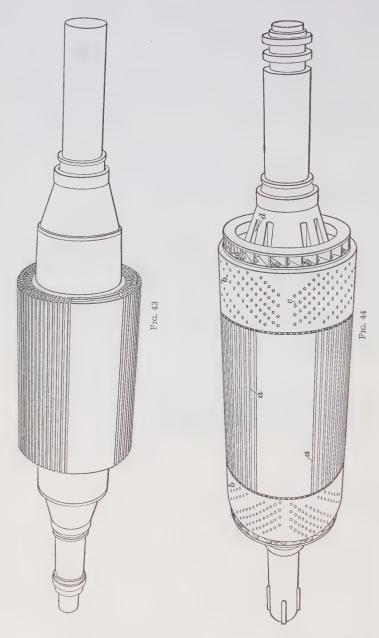


Fig. 42

the coil ends and bind them firmly in place. Ventilation of the coil ends is obtained through the perforations c and grooves d, the fans assisting in maintaining air circulation. No means are provided for admitting air to the body of the rotor, but the conductors are large enough to make the losses small, and the heat is absorbed and dissipated by the massive rotor body.

63. Solid-Body Rotor With Parallel Slots.—Fig. 45 shows the method of constructing a solid forged-steel, two-pole



rotor body with slots milled in parallel planes. These slots extend lengthwise and across the ends of the rotor body, so

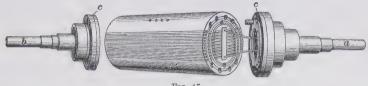
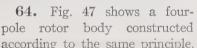


Fig. 45

that the field coils are entirely embedded. Fig. 46 shows a cross-sectional view of this rotor body. The coils a are copper

strips tightly wound in the slots and held by metal wedges b, this construction being used also across the ends. The journals a and b, Fig. 45, are turned with heavy shoulders that are bolted to the rotor body with intervening bronze disks c to prevent magnetic leakage from the rotor body.



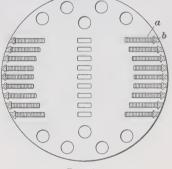
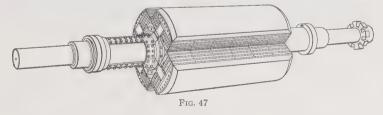


Fig. 46

according to the same principle, but with salient, or projecting, poles to permit greater space for copper. In this case,



the body and the shaft are in one piece; however, the journals are sometimes made separate, as in Fig. 45, in order to reduce the size of forging required.

MISCELLANEOUS PARTS OF STEAM TURBO-ALTERNATORS

Collector Rings.—In order to resist high centrifugal stresses and to obtain contact surfaces that run absolutely true, the general practice is to shrink forged iron or steel rings over steel shells with intervening mica cylinders about $\frac{1}{16}$ inch

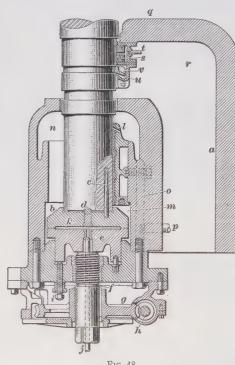


Fig. 48

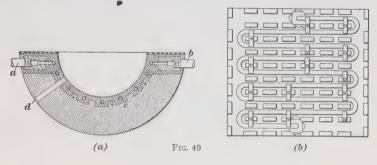
thick. The rings are heated and placed over the insulated shell, and, on cooling, they shrink tightly against it, making a very substantial construction. The shell is pressed and keyed on the shaft, and the ring surfaces are then finished true.

66. Bearings for Vertical-Shaft Steam Turbo-Alternators.—Fig. 48 shows a combination step and guide bearing, which is placed in the lowest part of the turbine base a. A rotating bearing plate b is attached to the

lower end of the shaft by pins c and key d. Below the rotating plate b is a stationary plate e supported on a screw f, by means of which the position of the whole rotating member can be adjusted by turning the worm-wheel g through the worm-screw and shaft h. Screws i serve to aline the stationary plate e with the rotating plate b. A pipe j extends through the adjusting screw to the annular space k between the rotating and stationary plates. Oil is forced into the space under a pressure of 500 to 800 pounds per square inch, which pressure is sufficient to lift the whole rotating element a few thousandths of an inch and float it almost frictionless. The mechanism thus far described constitutes the *step bearing*.

The guide bearing l is lined with bearing metal at the shaft surface. It is oiled by the overflow from the step bearing. Oil from the annular space k enters the chamber m with sufficient pressure to force it up between the shaft and the guide bearing to chamber n, from which it returns to the source of supply through a passage in the structure o, not shown, and pipe p.

The wall a of the base separates the condenser chamber q from the bearing chamber r. Chamber r is at atmospheric pressure, and chamber q at a pressure considerably below



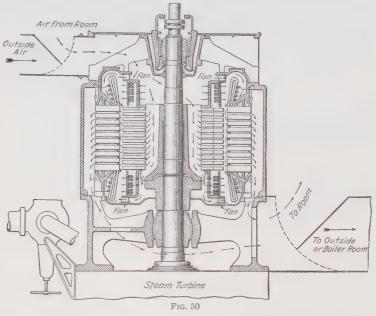
atmospheric pressure; therefore, a seal is necessary between the two. This seal consists of two carbon packing rings s that fit the shaft very closely, but do not bear against it with any pressure. As a further preventive, steam at slightly above atmospheric pressure is admitted through pipe t. The pressure around the packing rings being higher than in chamber r causes a very small flow of steam into the pan u, thereby preventing a flow of air in the opposite direction. All condensation is thrown by deflector v into the pan u and drained away. The set has two additional guide bearings, one between the turbine and the generator and the other above the generator; both are supplied with oil under pressure.

67. Bearings for Horizontal-Shaft Steam-Turbine Alternators.—In order to keep the bearings of large hori-

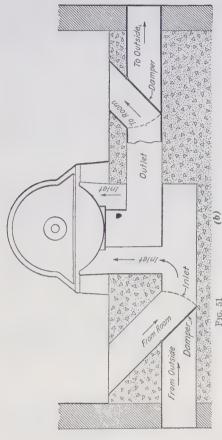
zontal turbo-alternators cool, special arrangements are essential. In some cases, oil is circulated through the bearings under pressure and also through separate cooling coils before returning it to the bearings; another plan is to circulate cooling water through pipes embedded in the bearing metal below the shaft, as shown in Fig. 49. In (a) is shown a cross-sectional view at the center of the lower half of the bearing, and in (b) is a development showing the arrangement of the cooling pipes before the bearing metal is poured over them. The inlet and the outlet for the cooling system are shown at a and b, view (a), and the sections of the pipes themselves can be seen at c. Oil enters the bearing under pressure at the opening d.

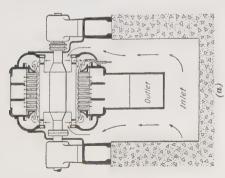
VENTILATION

68. The losses per kilowatt output are practically the same in the steam turbo-alternator as in others, but the output is so



much greater in proportion to dimensions that the losses per unit cubical contents are very high. Moreover, little space is





available in the turboalternator for ventilation. Special means are therefore essential for circulating air.

69. Vertical Turbo-Alternators.—Fig. 50 shows, by arrows, the circulation of air through a vertical turbine-driven alternator. By means of dampers, air can be taken in above the alternator either from outdoors or from the dynamo room, and, after passing through the machine, it can be discharged into the room if heat is needed or it can be diverted into the boiler room or outdoors. Fans at the ends of the rotating field cause air to circulate, as shown, through openings and ducts in the windings and cores so as to carry away the heat. The field construction of this particular alternator, with the fans removed, is shown in Figs. 41 and 42.

70. Horizontal Turbo-Alternators.—A general scheme for ventilating a horizontal turbine is shown in Fig. 51, in

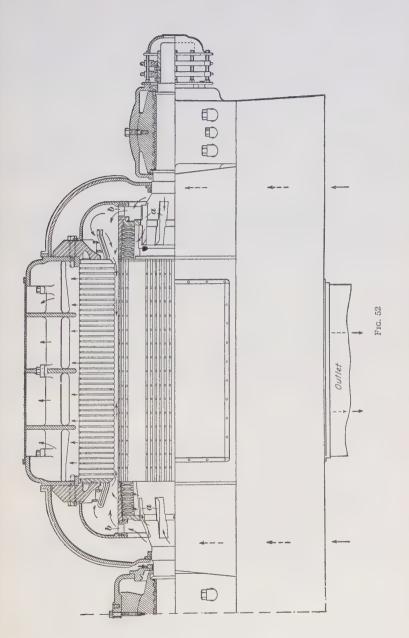
which (a) is a section in a plane of the shaft, and (b) a cross-section. View (a) shows, by arrows, the general circulation through the parts of the machine, and view (b) the possible sources and outlets of air for ventilation.

Fig. 52 shows more clearly how the air is made to circulate through the windings and the armature core of the machine for which the rotating field is shown in Fig. 44. Air enters from below the machine, as shown in Fig. 51; a small part of it passes through the grooves a, Fig. 52, near the rotor body and out through the coil ends and the holes in the protecting plates, where it joins the main current that has entered through the fans b. The arrows indicate the path through the air gap and the ducts in the stator core into the space inside the alternator casing, whence the discharge circulates around the machine and out at the bottom, as shown in Fig. 51. Holes are sometimes provided in the casing for discharging heated air directly into the engine room, although additional heat in the engine room is rarely necessary.

A salient-pole rotor, Fig. 47, acts as a fan; but it is usually equipped with axial fans to impel air into the spaces between the poles, whence it passes through the stator practically as shown in Fig. 52.

71. Air Supply.—For safe operation, the quantity of air should range from about 5 cubic feet per kilovolt-ampere output for ventilating small turbo-alternators to 2.5 cubic feet per kilovolt-ampere for large machines. At this rate of supply, the temperature of the air will be raised about 20° C. (68° F.) in the machine. For example, a 500-kilovolt-ampere machine requires approximately 2,500 cubic feet of air per minute, while a 25,000-kilovolt-ampere machine requires approximately 60,000 cubic feet.

The entering air should be cool and clean; a small percentage of moisture does no harm and does practically no good, although it may carry off a trifle more heat per cubic foot than dry air. The cooler the air entering the alternator, the lower will be the operating temperature of the machine or the higher will be the output for a given temperature.



- 72. Cleanliness of the air supply is very important. The presence of dust in the air causes deposits in the air passages, especially if the air also contains oil vapor. Air should therefore not be taken from a room in which reciprocating engines are operating, because the method of lubricating such engines produces oil vapor. The practice of taking air from outside the room in which steam turbo-alternators are operating is preferable and is general; discharging it oustide is also quite common. The air thus obtained is clearer and cooler than if taken and discharged inside, and the noise is greatly reduced.
- 73. In case the incoming air is heated and dusty, a device called a humidifier may be used. In this device the air passes through a chamber filled with a spray of water and is then forced through zigzag passages between metal plates. The free moisture and dust are removed and the air entering the generator is clean, cool, and free from water particles.

CONNECTIONS OF ALTERNATOR WINDINGS

FIELD CONNECTIONS

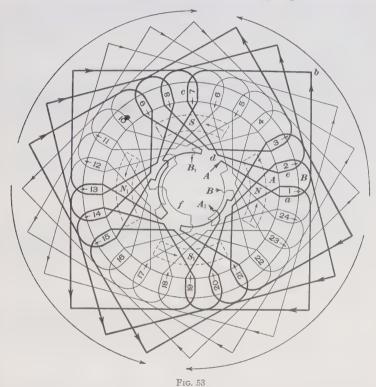
74. The field coils of an alternator are connected similarly to those of a direct-current generator, so that alternate poles shall have alternate polarity. Fig. 1 indicates the field connections of an alternator with rotating armature; the connections of a rotating field differ only in bringing the leads along the shaft to the collector rings, as at k, Fig. 29.

ARMATURE CONNECTIONS

75. Two-Phase Chart.—When removing windings from any electrical machine with the intention of replacing them, accurate records of connections should be made as a guide. If the desired connections of the armature of an alternator cannot be determined from the old windings, a chart should be

constructed and followed in making the new connections. The method of constructing this chart can be best explained by assuming a typical case and describing the chart construction.

Assume, for example, that a 24-slot stationary armature with two bars per slot is to be connected for two-phase output with a four-pole field. The number of slots per pole is six and



the number per phase per pole three. Each bar has a terminal at each end, and these terminals must be connected with corresponding terminals of other bars or with the external circuit so as to give the correct voltage and phase relations.

76. This armature core would have the general appearance of that shown in Fig. 4, though with fewer slots. Suppose a circle A, Fig. 53, represents one end of the inner cylindrical

surface of the armature and a circle B represents the other end. For convenience, call A the rear end and B the front end. Let all the rear-end connections be represented inside circle A and all the front-end connections outside circle B, and let the slot conductors be represented by short lines between the two circles, the two bars in each slot being represented by parallel lines; in reality, one conductor lies over the other in the slot. For convenience, the slots are numbered consecutively, beginning with any slot.

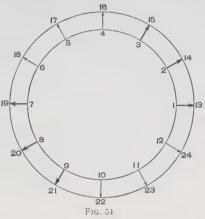
An instantaneous position of the rotating field can be indicated by dotted lines representing poles N, S, N_1 , and S_1 . At the instant indicated, conductors in slots 23, 24, 1, 2, and 3 lie in the field of pole N; those in slots 5 to 9, inclusive, in the field of pole S; those in slots 11 to 15, in the field of pole N_1 ; and those in slots 17 to 21, in the field of pole S_1 . The conductors in slots 1, 7, 13, and 19, being opposite the centers of pole faces, are cutting lines of force at the most rapid rate and hence generating highest instantaneous voltages. The voltage generated in slot 7 is directly opposite in phase to that generated in slot 1, or 180 electrical degrees from it, because one is opposite the center of a south pole and the other opposite the center of a north pole. Between these two slots are six equal slot spaces, and the phase difference between the voltages generated in adjacent slots is therefore $180 \div 6 = 30$ electrical degrees. On tracing counter-clockwise around the diagram, it will be seen that the first conductor in each slot is a top conductor and the second is a bottom conductor. For instance, conductor a in slot I is a top, and conductor c in slot 7 is a bottom conductor.

77. A diagram such as that shown in Fig. 54 is now drawn to show the phase relations of the voltages in the slot conductors. Conductors in slots l and l3, lying opposite centers of north poles, generate voltages in the same direction across the stator face, and this direction is represented by the arrow l-l3. Conductors in slots 7 and l9, lying opposite centers of south poles, generate voltage in a direction opposite, or 180 electrical degrees, from that of the voltage generated in slots l and l3; this direction is therefore represented by the arrow l-l9. The

voltages generated in other conductors are also represented by arrows drawn to represent the correct phase relation. For example, in slots 2 and 14 the voltage is 30 electrical degrees from that in slots 1 and 13, and the arrows 1-13 and 2-14 are drawn to represent this angle; the voltages in slots 3 and 15 are 30 electrical degrees from those in 2 and 14, etc.

78. After Fig. 54 is completed, the end connections can be represented in Fig. 53. The front terminal of a conductor in slot 1 must be connected with the front terminal of a conductor in which the direction of the voltage is opposite, in

order that the voltage in one conductor forward across the armature face shall be added to that in the other conductor backward across the armature face. According to Fig. 54, conductors in slots 7 and 19 answer this requirement, and either could be used. Assume that slot 7 is selected; then connecting lines abc, Fig. 53, are drawn, giving counterclockwise progression of the



winding. This selection is purely arbitrary. All the lines representing front-end connections can now be drawn symmetrically with lines $a\ b\ c$, connecting conductors in slots 2 and 8, 3 and 9, etc.

At the rear, the slot conductors must be connected in groups of three, because there are three slots per phase per pole. Bottom conductor c in slot 7 must be connected to a top conductor in a slot whose voltage is as nearly as possible 180° displaced. According to Fig. 54, the voltage in slot 2 or 14 is displaced 150° , and up to this point the top conductors in both these slots are unused. Slot 2 gives a lap winding (Art. 19) and slot 14 gives a wave winding (Art. 20), as can be seen by noting the positions of these slots on Fig. 53. By selecting

slot 2 and drawing lines c d, d e and corresponding lines connecting the rear ends of conductors in slots 8 and 3, the rear connections of one group of conductors are completed. This group traced in series is 1-7, 2-8, 3-9, and these conductors are joined so that their voltages are added, as is shown in Fig. 54.

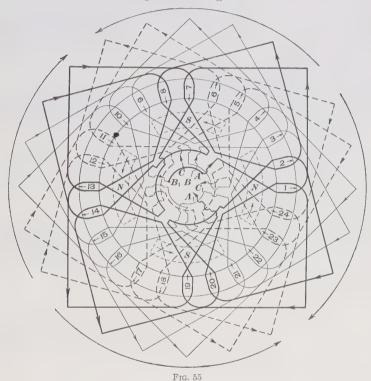
79. Winding Units and Winding Pitch.—A complete loop, or turn, as A a b c d, Fig. 53, is called a winding unit, or coil (see Fig. 8). The distance between the two sides of a winding unit is the winding pitch. If this distance in slots equals the number of slots per pole, the winding is called a full-pitch winding; if less than the number of slots per pole, it is a fractional-pitch winding.

The winding represented in Fig. 53 is a full-pitch winding. By tracing the circuit through the three winding units for which rear connections have been described, it will be seen that the slots traversed successively from phase terminal A at the rear are 1-7-2-8-3-9, terminating this group at the rear. This rear terminal of the conductor in slot 9 must be connected, according to Fig. 54, with a conductor in slot 15, requiring one of the pole connectors referred to in Art. 31 and shown in Fig. 20 (d). According to both Figs. 53 and 54, the other terminal from the rear of slot 9 should be connected with a terminal from slot 14, the remaining terminal from slot 8 with a terminal from slot 13, thus completing the second group of three winding units through slots 15-9-14-8-13-7.

According to Fig. 54, the remaining rear terminal from slot 7 should be connected with slot 13, and another group completed through slots 13-19-14-20-15 21. The remaining rear terminal from slot 21 should connect with slot 3, and the fourth and last group of three units in this phase completed through slots 3-21-2-20-1-19. Terminals A from slot 1 and A_1 from slot 19 are the terminals of what may be called phase A; this phase is indicated in Figs. 53 and 54 by heavy lines.

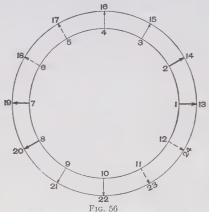
Phase B must be so connected as to generate voltage 90 electrical degrees from the voltage in phase A. According to Fig. 54, phase B should therefore begin in one of four slots 4, 16, 10, or 22. If slot 4 is chosen and reference is made to

Fig. 54 to determine proper phase relations of slot conductors, the connections of phase B may be completed in four groups, as follows: 4-10-5-11-6-12, 18-12-17-11-16-10, 16-22-17-23-18-24, 6-24-5-23-4-22. The phase terminals are B_1 and B. This completes a symmetrical chart, Fig. 53, which can be followed when connecting the winding.



80. The directions of currents in the units at the instant represented are as indicated by the arrowheads on the lines representing front-end connections, and the general directions through the several groups are as indicated by the long curved arrows outside the chart. These directions can be verified by noting that the electromotive forces generated in the conductors are from rear to front opposite north poles and from front to rear opposite south poles.

81. Three-Phase Connections.—In Fig. 55 is shown a chart for connecting a full-pitch winding to deliver three-phase

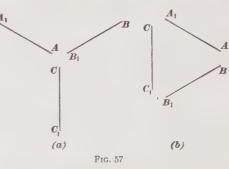


current. This chart is constructed by the aid of the phase diagram shown in Fig. 56. Its construction is the same as described for the two-phase chart, with the exception of the representation of the rear-end connections. In this case, there are two slots and two winding units per phase per pole, or four groups of two units each per phase.

By referring to both Figs.

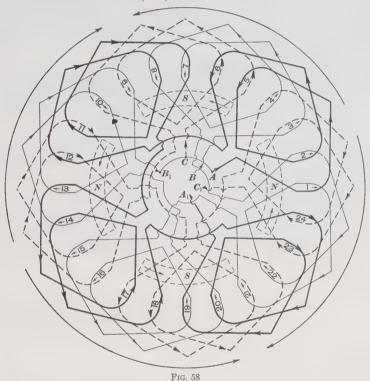
55 and 56 and connecting the rear terminals so that the electromotive forces shall be in the same general direction, a rear terminal from slot 7 is connected with a terminal from slot 2, completing one group of phase A, beginning with rear terminal A through slots 1-7-2-8. According to Fig. 56, one rear terminal from slot 8 can be connected with a terminal from slot 14 and the other with slot 13, completing the second group through slots 14-8-13-7. Connecting together the remaining rear terminals from slots 7 and 13 and the remaining terminal from

slot 14 with a terminal from slot 19 completes the third group through slots 13–19–14–20. The rear terminals from slot 20 are connected with the remaining rear terminals from slots 2 and 1, completing the last group of the phase



through slots 2-20-1-19 and ending the phase in rear terminal A_1 from slot 19.

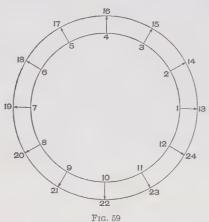
The connections of the other two phases are represented in a similar manner. The conductors must be so placed that the three voltages shall be 120 electrical degrees apart. According to Fig. 56, the proper phase relations are obtained by beginning the three phases in slots 1, 5, and 9, which are the slots chosen in constructing the chart, Fig. 55; the three phases thus end in terminals from slots 19, 23, and 3.



82. The three phases can then be connected in star \mathbf{Y} or in delta Δ , as indicated in Fig. 57. Each phase is here represented by a straight line with letters corresponding to those used in Fig. 55. For star-connection terminals, A, B₁, and C are joined as in Fig. 55 and as indicated in Fig. 57 (a); for delta-connection terminals, A₁ is joined to C, A to B, and B₁ to C₁, as indicated in Fig. 57 (b). Fig. 55 shows \mathbf{Y} connection.

83. Fractional-Pitch Winding.—Fig. 58 shows a chart for a fractional-pitch, three-phase, Y-connected winding, and Fig. 59, the time-phase diagram by the aid of which the chart is made. The winding units span only four slots or two-thirds of full pitch, thus including only a part of the flux. This winding gives lower voltage than a full-pitch winding, but is sometimes more desirable on large machines having few poles, because of shorter end connections.

In the construction of the chart, Fig. 58, a terminal



issuing from the front of a slot numbered I is indicated as connecting with a terminal from slot δ , and all other front connections are drawn symmetrically with this one.

84. In making the rearend connections, according to Fig. 59, they are joined so that the circuit of one phase, beginning with terminal A, Fig. 58, can be traced in four groups through the following slots: 1-5-2-6,

12-8-11-7, 13-17-14-18, 24-20-23-19, ending in terminal A_1 . The connections of the other two phases, terminating at BB_1 and CC_1 are similarly drawn. The three phases can be Δ -connected in the manner as described in Art. 82.

85. Charts for connections with any number of slots can be drawn on the same general plan. In every case the connections should be symmetrical; that is, the choice made where more than one way is available should be adhered to consistently. The winding units and the connections should be so made that in each case a terminal from the bottom of a slot connects with a terminal from the top of a slot. The connections at both ends of the armature should be so arranged that all terminals from bottoms of slots extend one way and all terminals from tops of slots extend the other way.

TRANSFORMERS

GENERAL DESCRIPTION

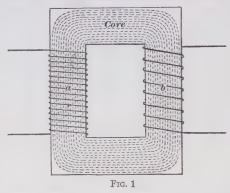
FUNDAMENTAL PRINCIPLES

1. A transformer is a device used on alternating-current circuits to change high-voltage energy into low-voltage energy, or vice versa. The action of the transformer is based on the fact that if the current varies in one of the two coils, say a, Fig. 1, wound on a magnetic core, an electromotive force is induced in the other coil b.

The coil supplied with current is called the *primary*, and the other coil in which the voltage is induced, due to the variation of the current in the primary, the *secondary*. Either of the two coils may be made the primary or the secondary, depending on which is connected to the source.

2. Further, the voltages applied and induced bear the same relation to each other as the number of turns of the primary bears to the number of turns of the secondary. For example, if the secondary has one-third as many turns as the primary, the induced voltage will be one-third of the applied voltage; if the secondary has three times as many turns as the primary the induced voltage will be three times the applied voltage.

With current in the secondary coil, a current must also exist in the primary coil; and the two currents are always of such values that the product of the secondary current and the secondary voltage is approximately equal to the product of the primary current and the primary voltage. These conditions would exist in an ideal transformer, that is, one having



no losses; but all commercial transformers have some losses due to resistance, hysteresis, etc. that modify the ideal conditions to some extent.

3. General Formulas.—The essential parts of a transformer, as represented by Fig. 1, are a rectangular iron

core, forming a magnetic circuit, and two coiled conductors a and b interlinked by this circuit. When one of the coils, say a, is connected with a source of alternating voltage, this coil becomes the primary and receives from the source a magnetizing, or exciting, current, which causes alternating flux in the core. This flux interlinks both coils and induces in them electromotive forces as follows:

$$E_p = \frac{4.44 \ \Phi \ N_p f}{10^8}, \tag{1}$$

and

$$E_s = \frac{4.44 \, \Phi \, N_s \, f}{10^8}, \qquad (2)$$

in which $E_p =$ effective value of induced electromotive force in the primary; $E_s =$ effective value of induced electromotive force in the secondary; $N_p =$ number of turns on the primary; $N_s =$ number of turns on the secondary; $\Phi =$ maximum value of the flux; f = frequency, in cycles per second.

If formula 1 is divided by formula 2, member by member,

$$\frac{E_p}{E_s} = \frac{4.44 \, \Phi \, N_p \, f}{10^8} \times \frac{10^8}{4.44 \, \Phi \, N_s \, f} = \frac{N_p}{N_s}$$
 (3)

The ratio of induced voltages in the windings is thus shown to be equal to the ratio of the number of turns. Formula 3 shows that from any alternating voltage any desired voltage can be obtained by means of a magnetic circuit interlinking two windings with turns proportional to the two voltages. The formulas given are for an ideal transformer, the losses not being taken into consideration.

4. The voltage induced in the primary, that is, the counter electromotive force, is practically equal to the applied voltage, and is 180 time-degrees from it in phase. These two voltages are considered equal, although the very small loss in overcoming resistance by the magnetizing current makes the induced voltage a trifle less than the applied voltage.

The value of the magnetizing current depends on the value of the flux that it must establish. If the magnetic circuit is of a comparatively high reluctance, for example if it is long and of small cross-sectional area or is made up of poor magnetic material, a larger magnetizing current will be required to establish the required flux than if the circuit were of large cross-section and of good magnetic material.

5. Influence of Current in Secondary.—Current resulting from induced voltage in the secondary, in other words the *induced current*, is 180 time-degrees behind the primary current, and this induced current in turn induces flux opposing that established by the primary current. The primary current therefore increases enough to overcome the demagnetizing effect of the secondary current, this increase being known as the *load current*.

The magnetomotive force due to a given current in a coil is proportional to the product of the current and the number of turns in the coil, or the *ampere-turns*. Therefore, in order to nullify the secondary magnetomotive force by the magnetomotive force due to the current in the primary coil, these magnetomotive forces must be equal and opposite.

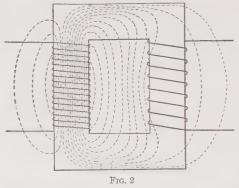
Let F_s =magnetomotive force of the secondary coil; F_p =magnetomotive force of the primary coil; F_m =part of F_p necessary for magnetizing the core. Then, vectorially, $F_s = F_p - F_m$

At full load, the value F_m can be neglected, because it is so small a proportion of the total, leaving as approximately true the formula,

$$F_s = F_p$$

6. If the secondary ampere-turns were not entirely neutralized by an equal number of primary ampere-turns, the secondary current would cause a change in the core flux, and the induced counter electromotive force in the primary would no longer be equal to the applied voltage. This difference in the applied and induced voltages would act on the primary coil, increasing the primary current. Equilibrium would be reached only when the induced and applied voltages were equal; that is, when the secondary ampere-turns were neutralized by an equal number of primary ampere-turns produced by a current in the primary in addition to the exciting current.

In most transformers, the exciting current is small compared with the full-load current; therefore, very little error is introduced by assuming that the ampere-turns of the primary are



equal to the ampereturns of the secondary.

7. Influence of Magnetic Leakage. In a practical transformer, the ratio $\frac{E_x}{E_s}$ is somewhat greater than the ratio $\frac{N_x}{N_s}$ because of the fact

that some of the flux interlinking with the primary passes, or leaks, through the space between the two windings, as shown in Fig. 2, without interlinking the secondary.

At no load, this leakage flux is negligible, because the magnetic circuit offers a very much better path for the flux than the surrounding space. But with load, the primary and secondary

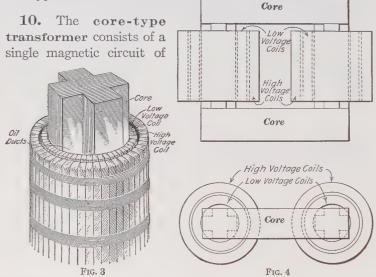
ampere-turns being opposed to each other, are jointly effective in producing an appreciable leakage flux. The reluctance of the air path being constant, the amount of leakage flux is directly proportional to the current in the windings. The flux interlinking both primary and secondary windings may be called useful flux in distinction from the leakage flux that interlinks the primary winding only. The induced voltage in the primary is therefore made up of a voltage induced by the useful flux and a voltage induced by the leakage flux. The latter voltage is called the reactance volts, or reactance drop, in the transformer.

8. Influence of Resistance of Windings.—When the transformer is loaded, a small part of the primary voltage is consumed in overcoming the resistance of the primary winding. This causes the induced counter electromotive force of the primary to be slightly smaller than the applied voltage. Similarly, the voltage induced in the secondary is always larger than the terminal voltage of the secondary windings, on account of the resistance of the secondary windings. If the load of the secondary is non-inductive, the voltage drops due to resistance are in phase with the terminal voltages; therefore. the primary induced voltage can be determined by subtracting arithmetically the primary resistance drop from the applied voltage, and the induced secondary voltage can be obtained by adding arithmetically the secondary resistance drop to the secondary terminal voltage. If the load is inductive, proper consideration must be given to the phase angle. In well-designed transformers, the resistance drop in each winding is from ½ to 1 per cent. of the normal induced voltage.

STRUCTURAL FEATURES

TWO-COIL TRANSFORMERS

9. Transformers may be classed roughly as two-coil and single-coil types, the latter being more generally called autotransformers. The general principles and many of the structural features are the same for both types. The word transformers nearly always refers to the two-coil type; the distinctive features of autotransformers will be described under a separate head. According to the shape of their cores, transformers may be classed as core type, shell type, and distributed core type.

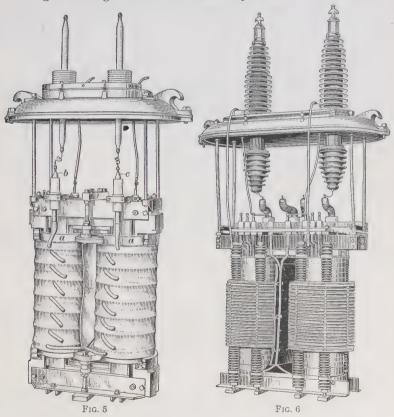


square, rectangular, or cruciform cross-section, with a rectangular opening, or *window*, to accommodate the windings. Fig. 3 shows one leg of a transformer of which the core has a cruciform cross-section.

The windings, which are usually of cylindrical shape, are placed on the two legs of the magnetic circuit, surrounding them

entirely. Relative positions of the windings and core are shown in Fig. 4. The low-voltage coils, unless large and heavy connections prevent, are usually placed next to the core, and the high-voltage coils are external and concentric with them.

A transformer of this type is shown in Fig. 5. The high-voltage windings are outside and separated from the low-

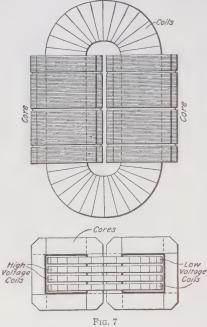


voltage windings by the insulating cylinders a. The high-tension winding consists of several form-wound coils, all of which are taped together and connected in series. As viewed from above, the conductor connected to terminal b passes through the window in a counter-clockwise direction and winds in many turns around that leg of the core. The last turn con-

nects to the bottom turn on the other leg, and the turns are wound on this leg clockwise, ending finally in the terminal c.

In this manner, all the turns act together in magnetizing the core in one direction. The secondary connections are made on the other side of the transformer, the coils consisting of a heavy conductor wound around each leg.

The high-voltage winding of the transformer shown in Fig. 6 is composed of several disk-shaped coils and is called the disk-type winding. Each coil is wound spirally with one



turn per layer, being spaced from its neighbors by insulating strips so as to provide horizontal oil ducts. This particular transformer is insulated for 115,000volt service.

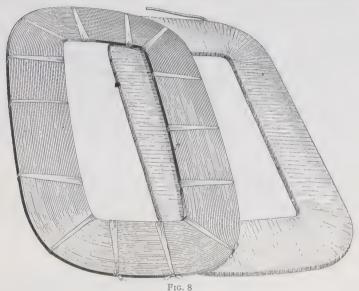
The practice on coretype design has changed so that now core-type construction is very largely employed, both here and abroad, on all sizes above 100 kilovolt-amperes.

11. The shell-type transformer, Fig. 7, is distinguished by a divided magnetic circuit, all coils being on one leg. The middle leg is usually divided,

as shown, virtually making two core-type magnetic circuits in multiple, but it is sometimes constructed of sheets cut the full width of the leg.

The windings on the shell-type transformer are usually of so-called *pancake* construction, shown in Fig. 8, the groups of high- and low-voltage coils being alternated in order to reduce the reactance. In the pancake windings, the conductor is usually wound spirally to the required number of turns per

section, two of these spirals, or sections, being assembled as one coil with an insulating collar separating the sections. The shell-type construction is usually employed on air-blast transformers. It is also usual on transformers of oil- or water-cooled types on the largest capacities, or where very heavy currents are desired. A good idea of the construction of a large shell-type transformer is obtained from Fig. 9. The assembled primary and secondary coils are boxed in with insulation, and



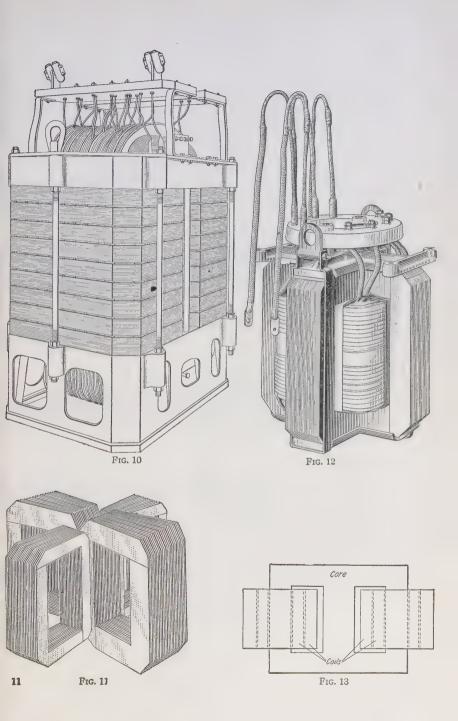
the surrounding magnetic circuit is being laid up sheet by sheet. A view of the assembled transformer without the tank is shown in Fig. 10.

12. In the distributed-core transformer, the magnetic circuit usually consists of a five-legged structure, as is shown in Fig. 11. The coils are assembled concentrically on the central leg, the outer four legs being uniformly disposed outside of the windings. There are thus four magnetic circuits in multiple. The construction and location of high- and low-voltage coils are generally the same as in core-type transformers. The distributed-core construction is usually employed on small

low-voltage transformers, say, up to 100 kilovolt-amperes. Fig. 12 shows the most common form of this transformer.



13. A polyphase transformer, which is a combination of single-phase transformers into one two-phase or one three-phase unit, is sometimes used on a polyphase circuit instead of single-phase transformers.



14. The two-phase unit is rather uncommon, as it is customary to employ two single-phase transformers for commercial two-phase work. The magnetic circuit of a two-phase, core-type transformer is shown in Fig. 13. This circuit is of precisely the same form as that of a single-phase shell-type transformer. In that case, however, two outer legs serve sim-

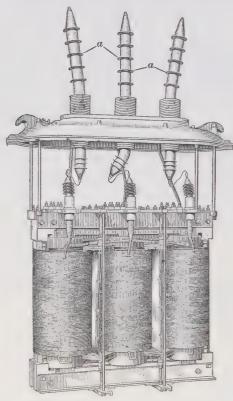


Fig. 14

ply as parallel paths for the flux, while in a two-phase unit each outer leg carries a flux differing in phase by 90 time-degrees from the flux in the other. The middle leg serves as a return path for these fluxes, and as their resultant is 1.41 times greater than either of the two fluxes. the cross-sectional area of the middle leg must be 1.41 times greater than that of either outer leg.

15. The threephase transformer is a highly efficient combination of three single-phase units.

In Fig. 14 is shown a view of a core-type,

three-phase transformer without its tank. The magnetic circuit consists of three equal legs that are joined at the top and the bottom, as shown in Fig. 15. The legs $a,\ b,$ and c carry three fluxes differing in phase 120 time-degrees. Since the vector sum of three fluxes 120 time-degrees apart is zero, no return circuit is required.

Three-phase transformers are of either the shell or the core type. Three-phase, distributed-core transformers have been built commercially, but they consist merely of three singlephase units placed one over the other and mounted as one unit in the tank.

16. Advantages and Disadvantages of Polyphase Transformers.—Owing to the fact that the different magnetic circuits of two- or three-phase transformers are partly combined, a polyphase transformer of a given kilovolt-ampere capacity employs less material and occupies less floor space than three single-phase transformers of the same combined kilovolt-ampere capacity. Moreover, the cost and weight of the polyphase unit is generally less than its equivalent capacity in single-phase transformers.

Because of the fact, however, that in case of breakdown on one of the phases, the cost of repairs is greater for the polyphase

unit than for one of the singlephase units, and that the cost of a spare polyphase unit is greater than that of one of the single-phase units, the tendency has been to discredit the use of polyphase transformers. However, the art of transformer manufacture has now advanced to

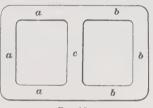


Fig. 15

the point where there is so little likelihood of breakdown under ordinary conditions that such argument has very little weight. As a result, the polyphase transformer is used more and more extensively.

17. Features Common to All Types.—From the foregoing descriptions, it may be summed up that the terms core type, shell type, and distributed core refer to the arrangement of the magnetic circuit. In the core type, the magnetic circuit forms a core to the coils; in the shell type, it forms both a core and a protecting shell to the coils; in the distributed-core type, the core is distributed around the coils.

In the assembly of the three types of cores, the general practice is to lay up the laminations so as to give lapped joints at

the corners. However, the use of butt-jointed cores is common in foreign practice, and is being employed here and there in the United States. Butt joints require very careful assembly and rigid clamping in order to prevent chattering, or buzzing, of the laminations.

On all types, high- and low-voltage windings are carefully insulated from each other by the use of heavy pads of varnished cloth, mica, and the like, and on all but the smaller sizes, additional insulation is secured through the use of ventilating ducts. It is particularly important that the insulation between high- and low-voltage coils have a high factor of safety, because, in case of failure, not only is the transformer put out of service, but the introduction of the high voltage to the load side where the devices are insulated for low voltages may involve loss of life. For this reason, in lighting transformer work, a test of at least 10,000 volts is applied between the coils, and when the line voltage is over 5,000 the test voltage is made twice the line voltage.

18. In addition to withstanding electrical stresses, the windings of a transformer are subjected to considerable mechanical stress when carrying current, owing to the electromagnetic repelling action set up by the currents in high- and low-voltage coils. The forces due to this action vary with the square of the current, and, consequently, under short-circuit conditions, are of very large magnitude. Unless the reactance in the circuit is sufficient to limit the current during short circuit to, say, ten to twenty times normal, these forces in large power transformers connected to big systems may amount to many tons and may result in the complete mechanical breakdown of the transformer, bending the coils and distorting them from their normal position.

Good practice demands very solid construction for the windings of a transformer. Before assembly, they are thorougly impregnated with a liquid insulating compound, which penetrates all parts of the windings, binding together the various turns and layers. This is accomplished by baking the coils in a tank from which the air is exhausted, then filling the

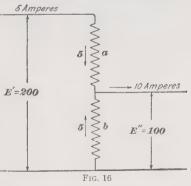
tank with hot insulating compound, and applying a pressure of from 75 to 100 pounds per square inch. The heat and the vacuum remove the moisture and air from the coils, and the pressure then forces the liquid compound into all the cores and crevices, where it hardens on cooling and becomes a solid mass. This compound not only strengthens the coil mechanically, but it improves the insulation and helps to conduct heat away from the interior of the coil.

When assembled, the coils must be carefully centered on the cores and rigidly blocked in this position so as to prevent any movement under the stresses due to heavy currents.

AUTOTRANSFORMERS

19. An autotransformer is a transformer having only one coil with which both the primary and secondary circuits are connected. For example, in a single coil connected across a 200-volt circuit there is a counter voltage of 200 and in half of this winding there is a counter voltage of 100; therefore, between one side of the circuit and the middle point of the

winding, as shown in Fig. 16,
there is a voltage of 100. By
thus eliminating the secondary
winding, a large saving in copper results. For example, with
a primary voltage of 200 and
a secondary voltage of 100, 10
amperes in the secondary line
and 5 in the primary are required to deliver 1 kilowatt.
In the part a that carries only
the primary current is 5 am-

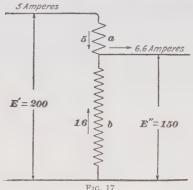


peres, and in the part b is the difference between the load current of 10 amperes and the current in a, that is, 5 amperes. Therefore, each part of the winding must be designed to carry 5 amperes, whereas with a transformer having two windings, the secondary copper would be proportioned to carry 10 amperes.

20. Fig. 17 shows what the conditions would be if the secondary voltage were 150. The secondary current would then be 6.6 amperes for an output of 1 kilowatt; the primary current and the current in the part a of the transformer in series with the primary circuit would remain 5 amperes, leaving 1.6 amperes for the remaining part b of the autotransformer. The copper in part b of the winding could therefore be made of a considerably smaller cross-section than that in part a.

In general, the more nearly the ratio of transformation is to unity, the greater will be the saving of copper resulting from the use of one winding instead of two.

21. In a two-coil transformer, all the energy supplied to the primary winding is transformed into magnetic energy and



then into electric energy in the secondary winding. In an autotransformer, only a part of the total energy is transformed, the rest of it being conducted directly to the secondary mains.

Of the total energy delivered by the primary mains, the fraction $\frac{E^{\prime\prime}}{E^\prime}$ is delivered direct-

Fig. 17 Iy to part b, Figs. 16 and 17, which, without transformation, transmits it to the secondary circuit. The remainder $\frac{E'-E''}{E'}$ is delivered to winding a,

transformed by means of magnetic induction, and delivered to winding b, which transmits it to the secondary. Therefore, an autotransformer transforms only the part of the total power represented by the fraction $\frac{E'-E''}{E'}$. The part of the winding

in series with the supply circuit, or part a, Figs. 16 and 17, is the primary winding, and the part b between the connections of the secondary circuit is the secondary winding. As in an ordinary transformer, the ampere-turns in these two parts are

equal and opposite. The smaller the part a of the winding, the smaller will be the energy transformed and the smaller will be the autotransformer for a given delivery of secondary power

Autotransformers, like two-coil transformers, can be used either to step up or to step down voltage.

LEADS

- 22. Transformer leads serve to connect the windings of the transformer to the line. On low-voltage units, the leads are made of a piece of flexible cable, which is brought out of overhanging covers fitted with porcelain bushings, as is shown later.
- 23. When the voltage exceeds 15,000 to 20,000, stiff leads are employed, and these pass out through the cover. For moderate voltages and indoor service, leads insulated with varnished cloth are often used, as in Fig. 5, in which the leads are shown projecting through porcelain bushings in the transformer cover. The distance over the surface of the lead between the high-tension connection and the tank is known as the creepage distance. If a discharge takes place, it is usually over this surface, and to guard against it, this distance is increased by insulating collars, as shown at a, Fig. 14. For outdoor service on moderate voltages, leads fixed in porcelain insulators are very widely used.

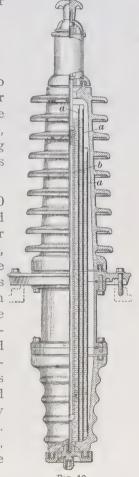
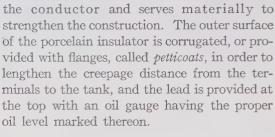


Fig. 18

24. When the voltage exceeds, say, 70,000, the conductor may be mounted in porcelain insulators filled with oil, as shown in Fig. 18, in which part of the terminal is cut away to show

the interior construction. The oil space is divided concentrically by thin insulating cylinders a. A metal rod b is used as



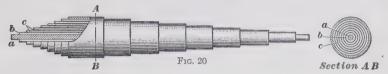
25. Another type of lead widely used for high-voltage work is the condenser-type terminal, shown in Figs. 19 and 20. The principle of this lead is that an alternating voltage applied to a number of condensers of equal capacity in series will be the same across each of the condensers, and will be equal to the total voltage divided by the number of condensers. Fig. 19 shows the appearance of the completed terminal, and Fig. 20 shows the construction.

In the condenser-type terminal, these condensers are built up as follows: On a metal rod a, Fig. 20, is rolled a layer of insulating material b, usually some specially impregnated paper; then, on this is rolled a sheet of tinfoil c of proper length, followed by another layer of the insulation, and so on until the proper number of condensers is obtained. As each condenser has a greater diameter than the one that precedes it, its length is shortened so that the capacities of all are as nearly equal as possible. This construction saves material, because every part of the insulation is subjected to approximately equal voltage stresses. If the insulation were solid without the tin-foil, the

inner layer of insulating material would be subjected to greater voltage stress than the outer layer, and the terminal would



not withstand so high voltage as would a terminal with tin-foil. In testing two leads of the same material and the same diameter, except that the tin-foil was omitted from one, this one broke



down at 120,000 volts, while the other withstood voltages up to 230,000 before failing. The metal disk a, Fig. 19, with well-rounded corners helps to equalize the voltage stresses on the condensers.

OPERATION OF TRANSFORMERS

COOLING

26. When a transformer is connected with a supply circuit, heat is developed in the transformer core, owing to

hysteresis and eddy-current losses. As the secondary current is increased, additional heat is developed, owing to copper losses in the windings. The maximum capacity of the transformer is the maximum load it can carry without developing heat enough to injure the insulating materials. This capacity can therefore be increased by employing means to cool the transformer. Among the means employed

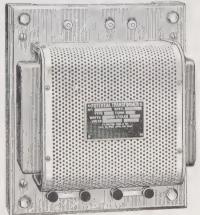


Fig. 21

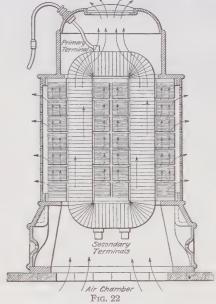
are self-cooling, air-blast cooling, oil cooling, oil-and-water cooling, and forced-oil cooling.

27. Self-cooled transformers are those of small dimensions, as shown in Fig. 21, in which the ratio of surface to

volume is so large that no special means of cooling are considered necessary. Their cooling is effected by natural air-currents created by the difference in temperature of the windings and the surrounding air and by direct radiation.

As the size increases, the ratio of surface to volume constantly decreases. The total loss and, consequently, the heat to be dissipated are proportional to the volume of material; therefore, the surface per watt loss decreases as the size of the transformer increases. Artificial cooling becomes necessary in





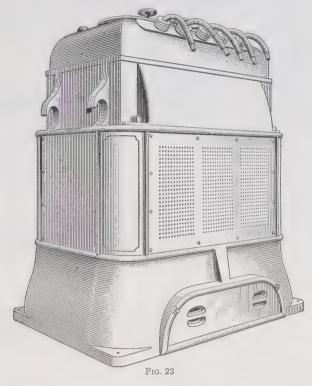
28. In the air-blast transformer, which is generally of the shell type, the heat is carried away by air-currents forced through ducts in the windings and the core. Air-blast transformers are mostly used in large central stations in which the voltages do not exceed 35,000.

Fig. 22 shows a crosssectional view, and Fig. 23 an external view, of such a transformer. Air at a pressure of $\frac{1}{2}$ to $1\frac{1}{2}$ ounces

per square inch is forced up into the base by blowers, passing out of the top and also through horizontal core ducts and the perforated sides. The quantity of air may be regulated by means of dampers in the vent holes of the transformer top. Usually, 150 cubic feet of air per minute is sufficient for each kilowatt of loss.

Clean, dry air should be used, and, ordinarily, the difference in temperature between ingoing and outgoing air should not be over 25° C. In case of failure of air supply, it is not safe to run the transformer with load except for very short periods;

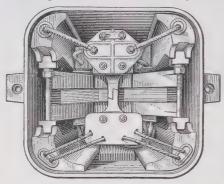
otherwise, the windings soon reach a dangerous temperature. For the same reason, an air-blast transformer cannot withstand a heavy overload except for short intervals. In ordinary service, the air ducts should be cleaned occasionally with compressed air to prevent clogging by dust; a pressure of 15 to 20 pounds per square inch will usually accomplish this.



29. Oil-cooled transformers are extensively used. The cores and coils of such devices are submerged in oil, which transfers heat from the windings to the outer tank. The oil next to coils is heated and, being lighter than cold oil, rises to the top, whence it circulates down the inner surface of the tank and is cooled. In addition to carrying away heat, the oil serves as an insulator between the various windings, and between the windings and the core. In fact, it would hardly

be possible to design a commercial, high-voltage transformer without the use of oil as an insulator.

30. Lighting transformers, Fig. 24, usually have a tank with a plain surface, this being sufficient to disperse the heat



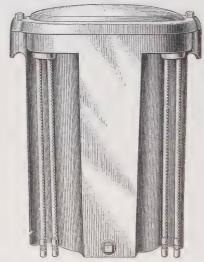


Fig. 24

carried to it by the oil. As the size of transformer increases, the plain surface of the tank becomes insufficient, and the surface is increased by the use of radiating ribs on cast-iron tanks, or by corrugating the surface of sheet-steel tanks, as in Fig. 25. Tanks of the latter type are made for transformers of capacities as high as 1,500 kilovoltamperes; the seams are welded and the ends of the corrugations cast into a cast-iron base and rim. Both Figs. 24 and 25 show the method of bringing out leads through porcelain bushings in overhanging covers, referred to in Art. 22.

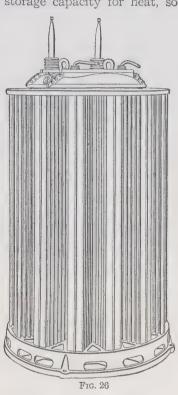
31. For large outdoor transformers, the compound corrugated tank, Fig. 26, and the

tubular tank, Fig. 27, are used. In the former, a very large surface is secured by providing large **V**-shaped corrugations that are in turn corrugated as on the medium sizes. In the tubulartank construction, Fig. 27, a large number of pipes are welded in at the top and the bottom of the tank. The oil circulates

through these pipes and is cooled very effectively by the surrounding air. The words *oil-insulated self-cooled* are frequently applied to transformers of this type, and the construction has been employed in units as large as 5,000 kilovolt-amperes.

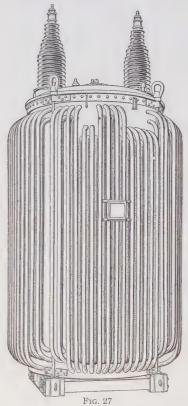
32. The use of oil in transformers affords the additional advantage of providing a large storage capacity for heat, so





that heavy overloads can be carried for short intervals without damaging the windings. The difference in temperature between copper and oil under ordinary operating conditions, is usually from 5 to 10° C., but this difference in case of overloads increases rapidly; that is, the temperature of the copper rises more rapidly than that of the oil. Therefore, ample allowance must be made if the temperature of the windings is to be judged

by that of the top oil in the transformer. The difference in temperature between copper and oil will be approximately proportional to the copper loss. For example, if at a full load the difference is 10° C., at 50 per cent. overload the copper loss will be $1.5^{2}=2.25$ times greater, and the difference will be $10\times2.25=22.5^{\circ}$ C.; that is, the temperature of the copper is

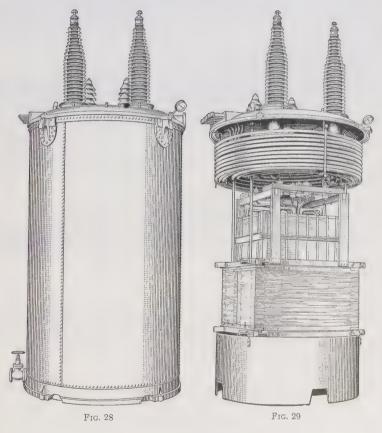


22.5° C. higher than that of the oil. Moreover, the temperature of the oil increases in proportion to the total loss.

33. A water-cooled transformer is one in which cold water circulates through coiled pipe in the oil surrounding the windings. This method of cooling is generally employed for transformers of 3,000 kilovolt-amperes and larger, because with these large sizes tank surface alone does not furnish enough radiating capacity. Oil and water cooling is also sometimes employed with smaller sizes, in which cases the tanks are made of cast iron. Tanks for the larger sizes are invariably made of boiler plate. The tanks are not depended on to dissipate heat; the circulating water carries it away. An external view of an oil-insulated water-cooled

transformer is shown in Fig. 28, and in Fig. 29 is shown the same transformer removed from the tank, giving a good idea of the position of the cooling coils. Practically any size of transformer can be built with this construction by increasing the length of cooling coil as the size increases, in order effectually to dispose of the heat developed.

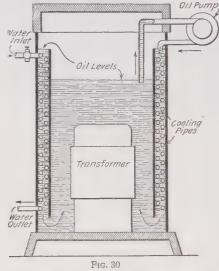
34. The temperature of the ingoing water is usually specified at 15° to 25° C., and the quantity is based on a temperature rise of the water of about 15° C., requiring about $\frac{1}{4}$ gallon per minute for each kilowatt loss. For continued overloads, the water rate should be increased, in order to limit the temperature rise. If the water supply fails, the transformer cannot be



operated with load except for a very short time. In such a case, even the core loss alone may be sufficient in some transformers to overheat the windings. In general, the temperature of the top oil in the center of the tank (the hottest part) should not exceed 75° C. Usually, large transformers are provided

with thermometers, and sometimes an electric bell and battery are arranged so as to sound an alarm whenever the temperature of the oil reaches, say, 65° C.

35. The cooling water often contains impurities of various kinds, for which reason an occasional inspection of the cooling coil should be made to see whether it is clogged up. The approach of this condition is usually indicated by a higher temperature rise of the oil and in aggravated cases by a restricted flow of water through the pipes. In removing the deposits, the water should first be blown out and the coils then filled with a solution of equal parts of hydrochloric acid and water.



on Pump. After standing an hour or so, this solution should be blown out; then, if all the scale is not removed, the operation should be repeated.

The cooling coils should also be inspected occasionally for a deposit that may form on their outer surface. This deposit is especially likely to form in case of long continued overloads, and it acts as a heat insulator, thereby causing higher operating temperature. It should

be carefully scraped off whenever found. If for any reason the oil is drained from the transformer, any deposit found on the windings can usually be removed by a jet of oil.

36. Forced-oil cooling means simply a means of artificially circulating oil in oil-insulated water-cooled transformers so large that natural oil circulation is too slow. The hot oil is pumped out of the top of the tank and returned to the bottom. Two methods of construction are in common use. The first requires only a pump and a motor for driving it; the second

method requires an additional cooling tank. Inlet and outlet pipes are required in both cases.

37. In the first method, which is shown diagrammatically in Fig. 30, the tank is of a double-wall construction, with the cooling pipes through which water circulates located between these walls. Hot oil is pumped from the top of the transformer to the space between the walls, so as to maintain a difference

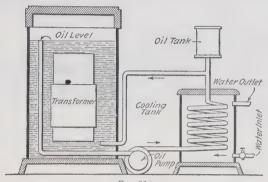


Fig. 31

in the oil levels of approximately 1 foot. This head causes downward circulation of oil over the cooling pipes, and the cooled oil is directed to the bottom of the windings, whence it rises as the heating goes on.

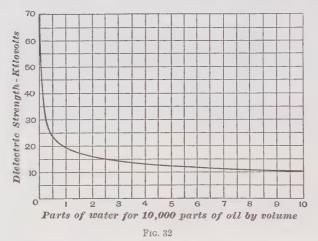
38. In the second method, shown diagrammatically in Fig. 31, the oil is circulated through the cooling coils located in the tank through which cold water circulates.

TRANSFORMER INSULATION

39. Transformer oil is a mineral oil obtained by partial distillation of petroleum. Such oil must not be easily ignitible; the temperature at which the ignition occurs, or the *flash point*, must be well above any temperature liable to be attained in service. Good transformer oil possesses a dielectric strength of 200 to 250 volts per mil. Samples of oil are usually tested between disks $\frac{1}{2}$ inch in diameter and spaced $\frac{12}{0}$ inch (200 mils)

apart, this being known as a *standard gap*. Good oil will break down at 40,000 to 50,000 volts on such a test.

40. Transformer oil must be absolutely free from moisture if used with even moderately high voltages. The effect of water on the dielectric strength of oil is very marked, as is indicated by the curve in Fig. 32. A sample of oil to break down at 40,000 volts on the standard gap may contain $\frac{1}{10}$ part of water in 10,000 parts of oil, by volume, yet the dielectric strength drops to less than 20,000 volts when there is 1 part of water in 10,000 parts of oil. With $2\frac{1}{2}$ parts of water for



10,000 parts of oil, the dielectric strength drops to 15,000 volts, etc.

Before placing a large transformer in service, a few samples of oil from it should be tested, and after installation, samples should be tested periodically. Samples should be taken from near the bottom after the oil has been undisturbed for several hours. This can be done by thrusting a long open tube to the bottom, then closing it at the top with the hand and withdrawing it. The receptacle into which the sample is placed must be perfectly clean and dry. The samples should be tested in a standard gap if possible, or if a variable voltage is not available, the gap should be adjusted for at least 200 volts

per mil. A rough practical test consists in turning the tube with oil bottom side up, when the water globules, if present, will slowly descend. If water can be detected in this manner, or if the electrical tests show a dielectric strength much less than 200 volts per mil (for transformers operating at voltages under 40,000 volts, 150 volts per mil would be satisfactory), the oil should be dried.

41. Drying Transformer Oil.—Drying transformer oil may be effected by heating it to a temperature of 100° to 120° C. Heat may be applied by immersing steam coils in the oil, placing them at the bottom of the tank, where the water settles,

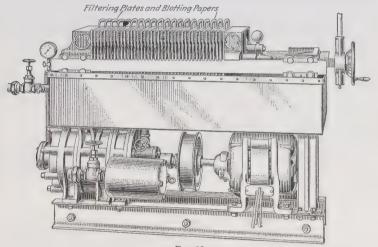


Fig. 33

or by placing a fire underneath the tank; in either case the water is vaporized and thus driven off. Another plan is to force hot air through the hot oil, the air being first thoroughly dried by passing through calcium chloride. Applying a vacuum to the tank and drawing the hot air up through all parts of the oil is also a fairly satisfactory method.

42. By far the best method of removing moisture from oil is by means of the *filter press*. This press also removes all dust and sediment, substances that materially lower the dielectric strength and that may clog the ventilating ducts.

Specially designed filter presses are built for this work, one of them being shown in Fig. 33. In this press, the oil is forced through several layers of a specially prepared blotting paper that are held between cast plates provided with a large number of filtering surfaces. Owing to the greater capillary attraction between paper and water than between paper and oil, the moisture is retained by the paper and the oil allowed to pass through. All the sediment is of course caught by the first layer. If the papers are removed frequently, every trace of moisture can be eliminated from the oil. For the best operation, the temperature of the oil should be between 25° and 75° C. By connecting the filter inlet to the bottom of the transformer tank and discharging back into the top of the tank, the filter press can be used for drying the oil of a transformer in operation.

- 43. Because water has such an injurious effect on the insulating qualities of transformer oil and other insulating materials, great care must be taken to keep moisture out of a transformer, especially one that is for high-voltage service. Such a transformer should not be allowed to stand out in the weather for a long time without excitation, even if it is designed for outdoor service. If the temperature of the interior of the transformer is kept a few degrees above that of the surrounding air, the effects of moisture will to a great extent be eliminated.
- 44. To prevent the admission of moisture to the windings during shipment, the practice of shipping transformers filled with oil is quite common where the excessive size and weight of the assembled unit is not prohibitive. To make sure, however, that the transformer is free from moisture before being put in service, the oil should be tested, even if it has been shipped in the transformer.

Where the windings are shipped out of oil, and the transformer voltage is greater than, say, 20,000, the windings should be carefully dried out before installation; this statement applies to large low-voltage units also.

Transformers using oil are in most cases provided with a gauge for determining the height of oil, the gauge being marked to show the proper oil level. The maintenance of this level

is very important for the proper operation of the transformer, particularly with the large self-cooled, tubular-tank construction previously mentioned; if the upper ends of the cooling pipes are uncovered, their function is entirely lost and the transformer will overheat.

Drying Transformer Windings.—Drying transformer windings can be accomplished in either of two ways. The first consists in forcing sufficient current through the windings to raise their temperature to approximately 80°C. This is done by short-circuiting one winding and applying sufficient voltage to the other to give the required current, ordinarily about one-fourth full-load current. The voltage required will approximate, say, 1 per cent. of the normal voltage for that winding. The temperature should be determined by the increased resistance of the windings, 1 per cent. increase corresponding to a temperature rise of approximately 2.4° C. In no case should the temperature exceed 80° C., corresponding to an increased resistance of approximately 33 per cent. If impossible to use the resistance method, use may be made of spirit thermometers placed in direct contact with the low-voltage coils. The transformer should preferably be out of its tank during this run, or the tank should be opened by removing all possible covers. Current should be maintained for at least 24 hours, and for very large transformers or high-voltage units, this time should be increased to 60 or 70 hours.

The second, and better, method consists in forcing heated air up through the windings, with the transformer in its tank. The temperature of the air should be approximately 80° C., and the process should be continued for at least 2 or 3 days, or longer if the windings are unduly moist. Heating outfits, each consisting of a blower and an electrical heater, are on the market for this purpose. Such outfits find a wide field for usefulness among large users of high-voltage transformers.

APPLICATION OF TRANSFORMERS

- 46. Transformers are also classified according to their application, the principal classes being power transformers, lighting transformers, measuring instrument transformers, series transformers for series street lighting, constant-current transformers, testing transformers, and miscellaneous applications. Each of these classes has some peculiar features of design and construction.
- 47. Power transformers, for stepping up or stepping down the voltage at the ends of transmission lines, are usually of fairly large size and are insulated for high voltage. Ruggedness of construction is of paramount importance in such transformers, for they are often subjected to heavy overloads and to abnormal increases in voltage due to lightning discharges, as well as to high-frequency stresses caused by switching the line on and off and by other disturbances. When installed outdoors, particular care is necessary to make the casings moisture-proof, and gaskets are accordingly used under all covers. For outdoor service the leads are generally special, usually having porcelain insulators. For high-voltage work leads of the oil-filled type or the condenser type are used.
- 48. Lighting transformers are in a majority of cases for outdoor service, being usually mounted on poles. They are invariably oil-cooled and usually of distributed-core construction. Both high- and low-voltage coils for such transformers are generally wound in two parts, and these may be connected either in series or in parallel, depending on the voltage requirements. Lighting transformers for use in manholes in connection with underground distributing systems should be of more rugged construction than those for mounting on poles. The casings of both manhole and pole-type transformers must be water-tight, and the connected or disconnected from the line without the necessity of opening the tank. An oil gauge is usually provided for determining the proper oil level.

49. Measuring-instrument transformers to reduce high voltage for safe use at switchboards and to reduce high alternating currents so as to avoid excessively heavy leads to switchboards are small potential transformers and current transformers. Instruments for use with such transformers have scales calibrated to read the line voltage or the line current to be measured.

A potential transformer of this type is usually oil insulated and is connected across the line. As the ratio of primary to secondary voltage should remain very nearly constant, such transformers must have low resistance and reactance. Fuses should always be connected on the high-voltage side of a potential transformer, and the low-voltage winding should be grounded in order to protect operators.

In a current transformer for use with an ammeter, the primary winding is connected inseries with the line, and the secondary in series with the ammeter. The voltage in the secondary circuit varies with the line current, and, the resistance of the circuit being constant, the current in the ammeter varies with that in the line. The iron loss in the transformer must be low in order that the magnetizing current may not appreciably affect the ratio of current transformation. Fig. 34 shows a common form of current transformer with the case opened.

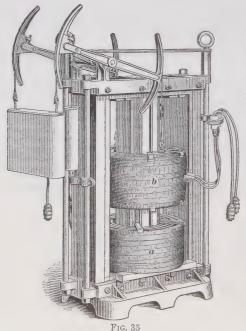
The primary current in a current transformer is the line current, which is unaffected by the secondary current. The secondary current, however, opposes the magnetizing effect of Fig. 34 the primary current, so that the resultant flux in the trans-

fore, be short-circuited before disconnecting the instrument.

however, opposes the magnetizing effect of Fig. 34 the primary current, so that the resultant flux in the transformer is low, causing low induced secondary voltage. If the secondary circuit is opened, the flux becomes high, causing high induced voltage and usually a breakdown of the insulation. The secondary winding of a current transformer should, there-

50. Series transformers are also used in street lighting where incandescent lamps are in series, a small transformer being used with one or more lamps. The primary is connected in series with the line and the secondary across the lamp.

Means for automatically short-circuiting the secondary winding in case of a lamp burn-out are usually provided in the form of a thin insulating film between two spring contacts in parallel



with the lamp. When the circuit opens and the voltage across the secondary rises, it punctures the film, thereby short-circuiting the secondary.

current transformers are used in series arc-lighting circuits in which the current must remain constant while the number of lamps in series varies. Fig. 35 shows the appearance of such a transformer removed from its oil tank. The stationary primary coil a is connected to a

source of alternating electromotive force, and the movable secondary coil b is connected to the lamp circuit. In order to maintain constant secondary current, the voltage of the secondary must vary with the number of lamps. The constant secondary current in different circuits is usually some value between 4 and 7.5 amperes, depending on the character of the lamp. On increasing the resistance of the secondary circuit by switching on additional lamps, the current automatically adjusts itself by changing the relative position of the secondary and primary coils.

The secondary coil is suspended, as shown, from a counterbalanced rocker-arm. The tendency of the coil to move toward the primary is opposed by both the counterweight and the magnetic repulsion between the coils caused by the current. At full load, the coils are only an inch or two apart. If the resistance of the secondary circuit is decreased, the momentary increase in current results in a greater repulsion of the coils

and they move farther apart. The separation of the coils in turn results in an increased leakage flux, thus reducing the useful flux through the secondary, and the voltage decreases to correspond to the reduction in load.

52. Larger constantcurrent transformers than shown in Fig. 35 are provided with two secondary coils, one above and one below the stationary primary, as shown in Fig. 36. The secondary coils are counterbalanced and move toward or from the primary as the resistance of the secondary circuit becomes greater or less. A separate

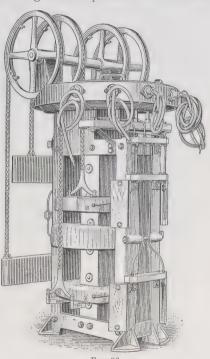


Fig. 36

circuit of from 50 to 75 arc lamps each can be operated from each secondary coil, and the current in each circuit can be adjusted to remain constant at a value independent of the current in the other circuit. This value is adjusted by changing the counterbalance weights.

When switching on a circuit of lamps, the moving element should be set for minimum voltage (maximum leakage) in order to prevent excessive initial rush of current. In some cases, a latch is provided automatically to hold the secondary coil in position for maximum leakage until the lamps have started.

53. Testing transformers are used in making dielectric strength tests of materials, such as oils and other insulators.

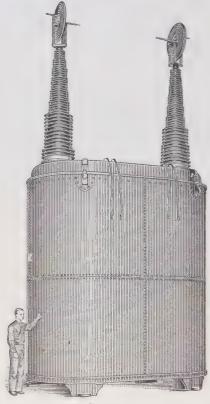


Fig. 37

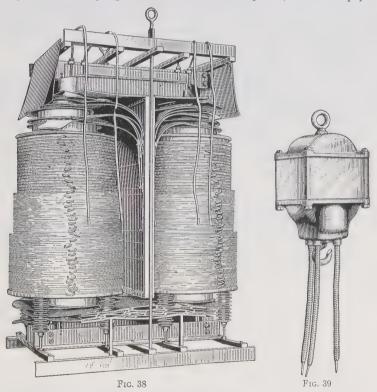
The low-voltage coils of such transformers are made to suit the voltages of ordinary lighting or power circuits, and the high voltage coils may range from 10,000 volts up to possibly several hundred thousand volts.

Testing transformers are of the oil-cooled type, and special attention is given to their insulation. Fig. 37 shows a testing transformer for a maximum secondary voltage of 750,000 and, therefore, capable of producing a spark between needle points set over 6 feet apart. Extralarge, oil-filled leads are required to bring out the terminals of the high-voltage winding, and these are surmounted with choke coils for protecting the end

turns of the transformer from high-frequency oscillations. The interior view, Fig. 38, shows the core-type construction and the extra-heavy insulation. A very large number of high-voltage coils are connected in series, the diameters decreasing toward the top of the legs as the voltage difference between legs increases. The low-voltage coils are placed next to the

core, separate leads being brought out from each of the two coils, so as to enable their connection in series or in parallel.

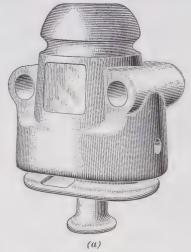
54. Among miscellaneous applications are transformers for electric furnaces and for welding, in which the secondary is bar wound, sometimes with only one turn, and capable of carrying several thousand amperes; also the pipe



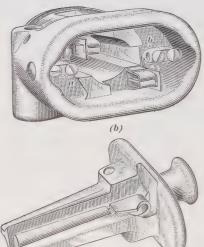
thawing transformer with variable external resistance for regulating the voltage; and the telephone insulating transformer to prevent injury to the operator by high voltages induced by proximity to power transmission lines.

55. A large class of transformers and autotransformers is used for reducing line voltage to some particular value best

adapted to the load device, such as sign-lighting transformers, where 110 volts is stepped down to, say, 25 volts for low-volt-



age tungsten sign lamps; or arc-lamp autotransformers, where 220 volts is stepped down to the voltage required for best operation of the arc. A small shell-type unit of this latter class is shown in Fig. 39. Another class of transformers and autotransformers is used for small work, such as ringing bells, running electrical toys, and lighting individual low-voltage lamps.



(c) Fig. 40

56. Fuse Protection.

Fuses, or cut-outs, are usually connected in series with the high-voltage winding of a lighting transformer, in order to protect the winding during short-circuits or other abnormal current conditions. Fig. 40 (a) shows a transformer cut-out that serves also as a disconnecting switch. The line and one end of the winding are connected to terminals a and b, as shown in (b). The removable part, which is shown in (c), is provided

with two blades fitting snugly into the terminals. The blades are insulated from each other, except as connected by a fuse wire that lies in a furrow c running around the end of the movable

part. The fuse is proportioned to melt and thus open the circuit at a predetermined current near the maximum that can be carried safely by the transformer windings.

CHARACTERISTICS OF TRANSFORMER

- 57. Regulation.—If a constant voltage is impressed on the transformer primary, the resistance and reactance drops cause the secondary terminal voltage to vary with variations in load. At no load, the voltages will correspond to the ratio of turns; as load is increased, the secondary voltage will become less; and as load is decreased, the secondary voltage will become greater. In transfermers that are supplying lighting circuits, this is particularly undesirable on account of the resulting unsteadiness in lights. A transformer in which the variation of secondary voltage is small from no load to full load when the impressed voltage is constant is said to possess good regulation.
- 58. In practice, the regulation is usually specified as the percentage increase in the secondary voltage of the transformer as the load is reduced from its normal value to zero. To determine the regulation of a transformer, a constant alternating voltage of the normal value should be applied to the primary, and the terminal voltage of the secondary should be noted both at no load E_s and at normal load E_{so} ; then

percentage of regulation =
$$\frac{E_s - E_{so}}{E_{so}} \times 100$$

In specifying the regulation of the transformer, it is necessary to mention the power factor at which this regulation is expected. For example, the regulation of a transformer may be satisfactory at unity power factor, but entirely unsatisfactory at a power factor of, say, 75 per cent.

59. Transformer Losses.—The energy delivered by a transformer is always less than the energy received from the mains, on account of the losses that take place within the transformer. These losses are:

- 1. The I^2 R loss, or copper loss, due to the resistances of the primary and secondary windings, which, in commercial transformers at full load, is usually from 1 to 2 per cent. of the power delivered.
- 2. The core loss, due to the alternating flux in the core; this loss is composed of two parts, hysteresis loss and eddy-current loss. Hysteresis loss is due to magnetizing the core first in one direction and then in the other; it is directly proportional to the frequency and depends on the maximum flux density and on the quality of iron used. Eddy-current loss results from the circulation of the currents induced in the core by the variation of the flux. To reduce the eddy currents, the resistance of their path in the core is made high by laminating the iron in the direction at right angles to that in which the currents tend to flow. All transformer cores are therefore made of thin sheet iron punchings, which are insulated from each other by thin sheets of paper, by coating them with some insulating substance, or by the scale that is usually produced on the sheets during the process of annealing. In this manner, the eddy-current loss is reduced to about 20 per cent, of the total core loss in the transformer. Eddy currents are proportional to the square of the frequency, the square of the maximum flux density, and the square of the thickness of the laminations.
- 60. A great amount of developmental work has been done on transformer iron for the purpose of reducing the losses. One difficulty, which has now been overcome, was due to the fact that the core loss of a transformer in service gradually increases. This characteristic, commonly known as aging, has been eliminated by the introduction of silicon. It has been found also that if transformer iron is made to contain almost 3 per cent. of silicon, the core loss is considerably reduced. This has given rise to silicon steel, which is now extensively used in transformers and particularly in lighting transformers. The core loss in silicon steel is about 75 per cent. of the loss in ordinary iron, when operating at the same flux density.
- 61. Determining Transformer Losses.—To determine core loss of a transformer, connect it to a source of low-voltage

supply, as shown in Fig. 41. The high-voltage winding is to be left open and the low-voltage coils are to be connected as for usual operation; that is, either in series or in parallel. In Fig. 41 the low-voltage coils are shown connected in parallel.

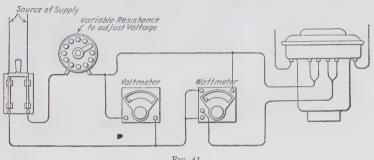


Fig. 41

The normal low voltage at the proper frequency is then applied to the low-voltage coils, and the wattmeter reading is the core loss.

To determine the copper loss, connect the transformer as shown in Fig. 42. The low-voltage windings are to be short-circuited, and the voltage should be so adjusted across

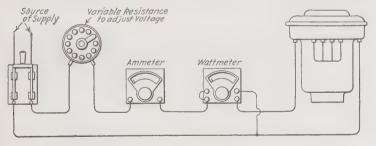


Fig. 42

the high-voltage coils that the full-load current is indicated by the ammeter. The wattmeter reading then indicates the fullload copper loss.

The total losses of the transformer are the core loss and the copper loss.

63. Efficiency.—The efficiency of a transformer may be calculated as follows:

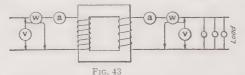
$$\textit{per cent. efficiency} = 100 \times \frac{\textit{energy output}}{\textit{energy input}};$$

or, if the losses are known,

per cent. efficiency =
$$100 \times \frac{\text{energy output}}{\text{energy output} + \text{core loss} + \text{copper loss}}$$

The core loss is constant, taking place during the total time that the transformer is excited; on the other hand, the copper loss depends on the load, being small at light loads and increasing with the square of the load current. The relative amounts of the two losses depends on the class of service for which the machine is designed. If the transformer is connected continually to the exciting mains, but is loaded only part of the time, the core loss becomes a much more important consideration than the copper loss.

64. Efficiency Tests.—The characteristics of small transformers can be determined by a load test, the connections



being as shown in Fig. 43, in which ammeters are indicated at a, voltmeters at v, and wattmeters at w. Rated

voltage is applied to the primary, and the secondary load is adjusted to any desired value up to full capacity. The wattmeter on the primary side then indicates input and that on the secondary side, output; the difference between input and output

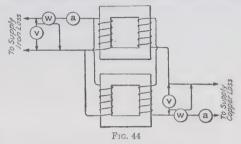
is the loss, and the ratio $\frac{output}{input}$ is the efficiency. The loss and

the efficiency at any load can be obtained in this way.

65. When it is inconvenient to load a transformer, the losses are determined separately, and from these the efficiency is calculated. Where two transformers of similar rating are available, they may be tested under actual load conditions by the so-called *leading back*, or opposition, method. The two transformers are connected as if for operation in parallel,

as described later, and the external connections are made as shown in Fig. 44, in which the reference letters have the same

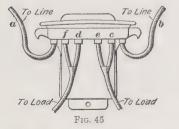
significance as those in Fig. 43. The low-voltage coils, Fig. 44, are connected in parallel and are subjected to their rated voltage; the high-voltage coils are connected in series and subjected

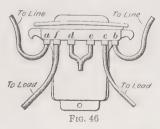


to voltage high enough to establish full-load current in them. The wattmeter on the low-voltage side then indicates the iron loss, in watts, and the wattmeter on the high-voltage side indicates copper loss, both these losses in this case being at full load. Proper frequency must be employed in both cases.

INTERCONNECTION OF TRANSFORMER COILS

66. Interconnection of Secondary Coils.—Each lighting transformer is usually provided with a low-voltage winding in two parts, in order to facilitate connection for two voltages; one voltage is obtained by connecting the coils in series and the other by connecting them in parallel. It is customary to bring out secondary leads in such order that they can be connected as in Fig. 45 for parallel operation and, as in Fig. 46, for series operation. Fig. 47 shows the coils and their con-

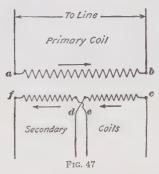




nections, the lettering corresponding to that on Figs. 45 and 46. The arrows indicate an instantaneous voltage condition.

The secondary voltage is always 180 time-degrees behind the primary voltage. If the primary and secondary coils are wound in the same direction and the leads are symmetrically brought out, the voltage from c to d and from e to f, Fig. 47, is thus always opposite in direction to the voltage from a to b. Therefore, to connect the two secondary coils in series, leads d and e must be joined, while to connect the coils in parallel, lead c must be joined to e, and lead d to lead f.

67. The primary and secondary leads are often brought out on opposite sides of the transformer instead of as shown



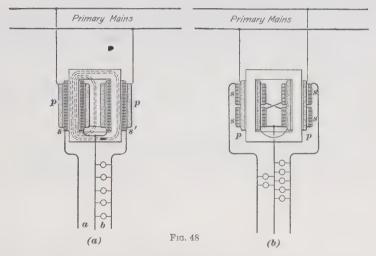
in Figs. 45 and 46, and the secondary leads are not always brought out in the order indicated in Fig. 47. For this reason, the connections MMMMM should always be checked as follows: Connect the primary winding to the line; next determine which leads belong to the same secondary coil by connecting one lead to an incandescent lamp and touching the other terminal of the lamp

to each of the remaining three leads, one after the other, until the lighting of the lamp indicates that the other terminal of the coil is touched. The bare wires of the primary leads are smaller than those of the secondary leads.

- 68. To connect the coils in series, temporarily join two leads, one from each coil, and connect the lamp, or possibly several lamps in series, between the two remaining terminals. If the lamps burn brightly, when the primary is excited, the coils are in series, their voltages being added. If the lamps remain dark, the two voltages oppose each other, showing that the connection is wrong for series connection. The rated voltage of the test lamp, or the series of test lamps, must equal or exceed the voltage to be tested or the lamp may burn out.
- 69. To connect the coils in parallel, temporarily join two leads, one from each coil, and connect the lamp between the

two remaining leads. If the lamp remains dark with this connection, while the primary is excited, the leads giving no light may be safely joined together and the temporary junction may be made permanent. If the lamp lights, the leads are improperly selected for parallel connection. These tests are important, for if the wrong leads are joined the transformer may be burned out.

70. Transformers on Three-Wire System.—When core-type transformers are used on a three-wire system, as shown in Fig. 48, the voltage on the two sides of the circuit

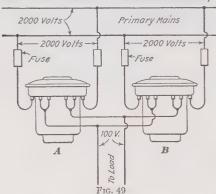


may become greatly unbalanced if the load is not equally divided. For example, in the extreme case, view (a), where the side a has no load, the secondary coil s will have no current and will therefore set up no counter magnetization, whereas coil s' will have a current due to the load on side b. Thus, the magnetic flux in the two sides of the core becomes unequal, as is roughly indicated by the dotted lines, and the secondary electromotive force is considerably higher on the side a than on the side b. In order to overcome this difficulty, the secondary may be wound in a number of sections s, view (b), and these coils cross-connected as indicated. The result is

that no matter how unbalanced the load may be, the demagnetizing effect of the secondary is the same on both cores and the voltage remains practically the same on both sides.

71. Operation in Parallel.—Transformers are often connected in parallel and the method of connecting is precisely the same as in connecting the two coils of the same transformer. Connect the primaries of both transformers to the line and interconnect the coils of each transformer separately in parallel or series, as the case may be; then treat the interconnected secondaries as single coils. Two transformers connected in parallel are shown in Fig. 49.

The two transformers to be operated in parallel must have the same ratio of transformation; otherwise, the secondary



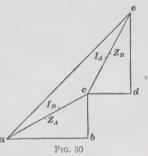
voltages will be unequal and the difference between the voltages will cause a current in the local circuit that joins the two transformers. This current induces a current in the primaries, and as the only opposition to it is the impedance of the two transformers, even a small

voltage may cause a heavy local, or short-circuit, current.

- 72. Sharing the Load.—Transformers connected in parallel should share the total load on all of them, in proportion to their ampere capacities. If they do not, the cause may be wrong connections or differences in voltage ratios; but the most common cause of unequal load division is difference of impedance. It is assumed that when two transformers with equal voltage ratios are operating in parallel, the current in each will be such that their impedance drops are equal.
- 73. The division of total current between two transformers connected in parallel may be predetermined graphically as

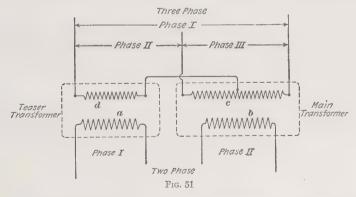
follows: From the values of resistance and reactance, the impedance triangles of the two transformers are drawn rela-

tively to each other, as shown in Fig. 50. The impedance triangle of the transformer A, Fig. 49, is represented by the triangle abc, and that of the transformer B, by the triangle cde. When two circuits are connected in parallel, the current divides in inverse proportion to the impedances. Thus, ac and ce, representing impedances Z_A and Z_B , ae respectively, represent the relative



values of the currents also; but ac represents the current I_B in the transformer B, and ce represents the current I_A in the transformer A; therefore, their resultant ae represents the total current in both.

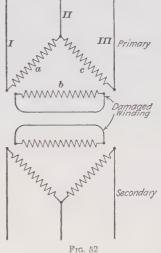
74. Phase Transformation.—Devices intended for operation on two-phase systems may be operated from three-phase circuits by means of transformers connected according to Scott's system of connections. By the same means, devices intended for three-phase circuits may be operated from a two-phase system. By the Scott system, two especially designed transformers are connected as shown in Fig. 51. The



two similar windings a and b are connected to a two-phase system, or device, and the interconnected windings c and d

are connected to a three-phase device or system. The winding c is called the *main winding* and the winding d, connected to the middle point of the winding c, the *teaser winding*. The number of turns in the teaser winding is only 86.6 per cent. of the turns in the main winding. The voltage and current relations of the Scott connection are explained in *Alternating Currents*, Part 2.

75. Polyphase Connections.—In three-phase systems, the separate phases of a three-phase transformer or of three single-phase transformers can be grouped into one of the four combinations:



- 1. High voltage \triangle ; low voltage \triangle .
- 2. High voltage \boldsymbol{Y} ; low voltage \boldsymbol{Y} .
- 3. High voltage △; low voltage ¥.4. High voltage ¥; low voltage △.

The fact should be noted that in any of these combinations at noninductive load the voltage and the current of each phase are in phase.

76. Transformers connected delta-delta possess the advantage that in case the winding of one phase is rendered inoperative, service can be maintained on the remaining two windings. The damaged winding should be completely

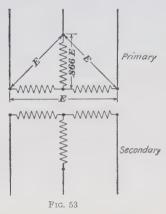
disconnected from the circuit in any case. In a three-phase coretype transformer, both the primary and secondary coils of the damaged winding should be left open; and in a shell-type transformer both these coils should be short-circuited upon themselves, as shown in Fig. 52.

The connection of two sets of transformer windings on a three-phase circuit, as in Fig. 52, is called *open-delta*, or **V**, *connection*, and is sometimes used as a regular three-phase connection. The voltages impressed across the two windings are the same as in the delta-delta connections. The currents in the windings, however, are changed, because the current in

line I or III has only one path, a or c, instead of the two paths, a and b or c and b, with the delta-delta connection. The

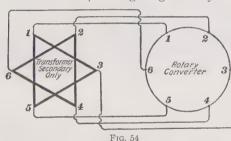
current in the windings is therefore equal to the line current.

77. The T-T connection, shown in Fig. 53, is sometimes employed for operating two single-phase transformers on a three-phase circuit. In order to use this connection, one transformer must be provided with leads from the middle point of each of its windings. Because of the fact that the T-T connection requires 50-per-cent. taps on one of the transformers,



this connection is not used so much as the V connection.

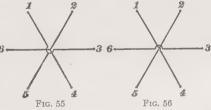
78. For operating large rotary converters, six-phase volt-



ages are very often employed. Such converters have six collector rings, across which are voltages as given in the diagram, Fig. 54. These voltages may be obtained from three-phase

voltages by employing transformers having two sets of secondary windings. The primary side may be connected either

Y or delta, and the secondary side may be in accordance with either Fig. 54 (delta-delta) or Fig. 55 (YY). The triangle 1-3-5, Fig. 54, represents one delta, and



the triangle 2-4-6, the other. Parallel lines as 1-5 and 2-4, are secondary windings in the same phase. In Fig. 55, 1-3-5 representations.

sents one \mathbf{Y} and 2-4-6, the other. Six-phase voltages may also be obtained from a single set of secondary windings by connecting each phase to diametral points in the rotary converter, as in Fig. 56. This is called *diametral connection*; 1-4 is one winding, the ends of which can be connected to the collector rings 1 and 4 of the rotary converter shown in Fig. 54.

ALTERNATING-CURRENT RECTIFIERS

VOLTAIC ARC AND STORAGE BATTERY

- 1. An electric, or voltaic, arc is a bow of intensely hot flame caused by the passage of electricity through space intervening between two electrodes. This flame may or may not be luminous, depending on whether anything that is luminous when heated is present in the arc; in some cases, one or both electrodes are heated until luminous. Opening any electric circuit in which electricity is flowing causes an arc; if this arc is very small, it is usually called a *spark*. To carry electricity across open space between electrodes requires voltage proportional to the length of the space, or arc.
- 2. A storage battery is a device for storing electricity. It is sometimes called an accumulator and, more rarely, a secondary battery. Properly, a battery consists of several cells, each cell containing two or more plates of metal or metallic compounds immersed in a chemical mixture in a liquid state, called an electrolyte. The plates are suspended in the electrolyte so that they have no direct metallic contact with each other except through an external circuit; they are equipped with terminals for the connection of electric conductors.

In passing through the cell, direct current traverses the electrolyte between the plates and causes chemical changes. The process of passing current through storage batteries by means of an external voltage is known as *charging* them. The plate by which the current enters the cell while charging is known as the *positive plate*, and that by which it leaves, the

negative plate. As the process of charging continues, the voltage across the battery terminals increases until it reaches a value beyond which little increase can be obtained; the battery is then said to be charged. During the process, chemical changes have occurred in the plate surfaces and in the electrolyte. These changes leave the materials in an unstable condition, such that if the positive and negative plates are connected electrically through an external circuit, the changes will recur, causing electricity to flow through the external circuit and through the cell in a direction the reverse of that followed while charging. This process is known as discharging the cell.

RECTIFYING DEVICES

CLASSIFICATION

3. Alternating current, on account of being so economically transmitted, is more commonly employed than direct current for lighting and for industrial motor operation. As direct current is essential for some purposes where the general current supply is alternating, means of changing from one kind of current to the other, that is, means of *rectifying* the alternating current, are in demand.

The various devices employed for this purpose may be classified as follows: *Mechanical* and *electromagnetic* combined, as motor-generators; *electromagnetic* alone, as rotary converters; *synchronous switching*, as synchronous commutating switches and mechanical, or vibrating, rectifiers; and *valvate*, as electrolytic rectifiers and rectifiers in which vapor arcs are used, a specific example being the mercury-vapor arc. Valvate devices depend for their operation on the peculiar characteristics of certain materials that act as valves, permitting current to pass in only one direction.

MECHANICAL AND ELECTROMAGNETIC RECTIFIERS

4. Motor-generators and rotary converters may be classed as mechanical and electromagnetic rectifiers. Both are general in application, being most used where comparatively large quantities of energy are to be converted. The motor generator, consisting of an alternating-current motor coupled, belted, or geared to a direct-current generator, receives and delivers energy at any desired voltage ratio; in a rotary converter, or synchronous converter, as it is frequently called, the ratio of direct-current voltage to alternating-current voltage is fixed. Motor-generators and rotary converters are described later.

SYNCHRONOUS SWITCHING RECTIFIERS

5. Synchronous commutating switches, or commutators running in synchronism with the alternating-current supply

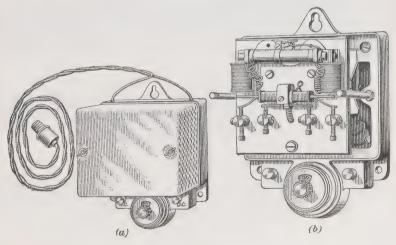
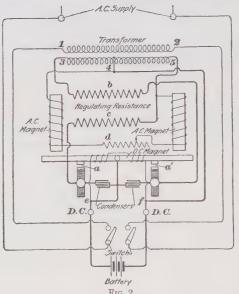


Fig. 1

system and operating in a manner similar to the commutator of a direct-current generator, are not a commercial success.

6. Mechanical, or vibrating, rectifiers are in successful use in small capacities for charging batteries of three or four cells each, such as are used for lighting and ignition in automobiles. These rectifiers consist essentially of switches that open and close automatically in synchronism with the alternating current that is being rectified. They operate in such a way as to intercept or rectify current half waves in one direction only.

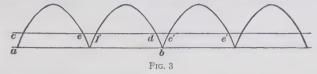
7. Fig. 1 illustrates one type of mechanical, or vibrating, rectifier, view (a) showing it complete, and view (b), with its



cover removed. Fig. 2 illustrates its connections and the principle of operation. The secondary of a small transformer is connected to two stationary platinumtipped contacts a and a' through regulating resistances b and c. Upper contacts a and a', are carried by a pivoted direct-current magnet that serves as the armature of two alternating-current magnets; these magnets are connected in

series with adjustable resistance d across one-half of the transformer secondary. The alternating-current magnets are so connected that, although their magnetic polarity changes with each current reversal, the same polarities are presented to the pivoted armature at every instant; that is, both are alternately positive and negative together as the current reverses. The armature is polarized by a direct-current winding connected with the battery being charged, one end being always positive and the other negative. Each end is therefore alter-

nately attracted and repelled by the poles of the alternatingcurrent magnet above, thus keeping the armature vibrating in



synchronism with the alternating current and making contact first on one side and then on the other.

8. These contacts close at proper instants to rectify each negative half wave, giving a pulsating direct voltage and current, as represented in Fig. 3. In order to operate with minimum sparking, the contacts are adjusted to make and break at instants when the current is zero. In Fig. 3 the line ab represents zero voltage, and the line cd, battery voltage. Only the rectified voltage above the battery voltage, or the part repre-

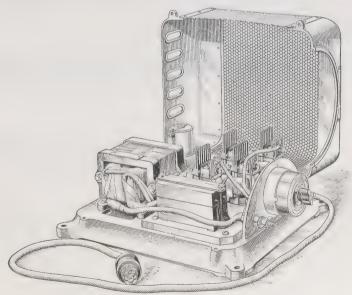
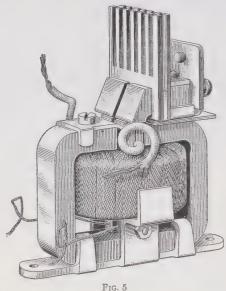


Fig. 4

sented by the curves above the line c d, is effective in charging. The contacts are therefore timed to close at instants ILT 384-9

corresponding to points c and f and to open at instants corresponding to points e and d. If either pair of contacts were closed at points below the battery voltage, the battery would discharge through the rectifier. The period represented by the space ef lapses between the instant contact is broken on one side and made on the other by the vibrating armature.

By this means, both alternating-current impulses, or both half waves, are utilized. One passes from point 3, Fig. 2, through the path b-a'-armature and pivot-e, where the cur-



rent divides, part passing through the battery and part through the directcurrent magnet to the point f, where the two parts unite and pass to point 4 of the transformer. The other impulse, starting from point 5, passes through the path c-a-armature and pivot-e, from which the return to point 4 is the same as before. The current from point e is thus continuously in one direction through the battery and the directcurrent magnet.

If the contacts a and a' are closed and opened at the exact instants of zero current, no sparking occurs. The resistor d serves to adjust the operation of the contacts and the condensers to remove slight tendencies to spark, so that the contacts remain uninjured for long periods. Springs keep the contacts open when the rectifier is not in operation, thus preventing battery discharge through these contacts. This rectifier delivers current to the battery in the right direction regardless of the connections to the battery, because the battery polarizes the armature; no attention need be paid to polarity when making

these connections, because both half waves are utilized. If the supply circuit is interrupted temporarily, the rectifier restarts automatically when the current is restored.

9. In Fig. 4 is illustrated another type of vibrating rectifier with the cover raised. Fig. 5 shows one vibrator in greater detail, and Fig. 6 shows connections. Current enters through a small transformer, which reduces the voltage to that required for the batteries. The secondary of this transformer feeds directly into the batteries through an automatic cutout and a

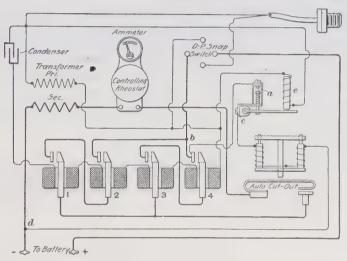


Fig. 6

series of contacts 1, 2, 3, and 4 that vibrate in synchronism with the current in the circuit, so that only the positive current waves reach the battery.

Each vibrator, as shown in Fig. 5, consists of a permanent magnet, an alternating-current magnet coil, vibrating steel armatures that carry massive removable carbon contacts, and a stationary copper contact with a comb top for heat radiation. The magnet coils, with a condenser in series, are connected across the primary circuit, as shown in Fig. 6. The combined effect of the permanent magnets and the alternating magnetism of the coils causes the armatures to vibrate in synchronism

with the current in the coils. The polarity of the vibrator changes in synchronism with the current, and the poles of the permanent magnet alternately attract and repel the vibrator as its polarity changes.

The operating coils of the automatic cut-out are in series with contacts a across the battery, the circuit from the + battery terminal being switch-b-a-c-cut-out magnet coils-d. Relay e is connected across the primary circuit, and when the rectifier is operating the relay core is held up, allowing contacts a to close the circuit through the cut-out magnet. The core of this magnet is drawn down, holding the cut-out closed. On failure of voltage, contacts a open and allow the cut-out to open, thus preventing battery discharge through the secondary coil of the transformer.

This rectifier utilizes only the positive-current waves, giving a current curve similar to Fig. 3, except with the alternate half waves omitted. In making connections to the battery, care must therefore be taken to have the polarity correct.

ELECTROLYTIC RECTIFIERS

10. Electrolytic rectifiers are also practical in small capacities; they are used for charging storage batteries, for electrotyping and electroplating, and for operating searchlights, electric bells, clocks, railway signals, etc., all on a comparatively small scale.

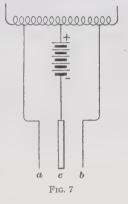
The electrolytic rectifier is of the valvate nature, and consists of a stoneware or metallic vessel containing an electrolyte solution in which are placed electrodes. Ordinarily, the solution is sodium or ammonium phosphate, or sodium bicarbonate. Three electrodes are commonly used, two of aluminum and one of some other conductor, such as lead, carbon, iron, or steel, that is not readily acted upon, or corroded, by the electrolyte.

11. Aluminum in such a combination possesses the peculiar property of building up a surface film that permits current in only one direction, namely, through the electrolyte to the aluminum, but not from the aluminum to the other electrode.

In other words, the action of this film is analogous to that of a valve. By connecting the aluminum electrodes a and b, Fig. 7, to two terminals of an autotransformer, or to the secondary terminals of a two-coil transformer, the other electrode c

to the negative terminal of a direct-current device, such as a storage battery, and the positive terminal of the device to the middle terminal of the autotransformer, direct current will be established in the consuming device when alternating voltage is applied to the autotransformer.

The voltage between the aluminum terminals, and, consequently, the voltage between the storage-battery terminals, can be adjusted by changing the relative positions of the autotransformer leads. The current through the battery is regu-



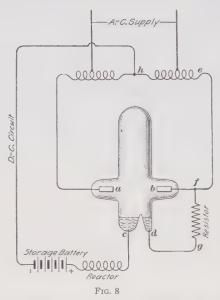
lated both by adjusting the voltage across the terminals of the aluminum electrodes and by adjusting the resistance in circuit with them. This resistance is sometimes adjusted by raising or lowering the aluminum electrodes in the electrolyte.

DESCRIPTION OF MERCURY RECTIFIERS

12. Nature.—The mercury rectifier also is of the valvate nature; it converts alternating current to direct current by means of an electric arc through mercury vapor. The essential part is a bulb, or tube, which is usually of glass with conductors that are sealed in the walls, and lead to electrodes inside. Pools of mercury, or quicksilver, in the bottom of the vessel form part of the electrodes, and above them are two other electrodes of graphite or iron suspended in separate chambers. The air is exhausted as completely as possible from the vessel, which is then hermetically sealed. The suspended electrodes are positive, or anodes; one mercury pool serves as the negative electrode, or cathode, and the other (or both others if there are two) serves as the starting anode.

13. Construction.—Fig. 8 illustrates a typical arrangement. The anodes, which may be of iron, graphite, or any substance that will not amalgamate (combine in an alloy) readily with mercury are shown at a and b; the mercury pool serving as negative electrode or cathode is shown at c; and the mercury pool serving as the auxiliary positive electrode for starting only, at d.

These vessels assume various forms, depending on the designer and on the service for which they are intended. The anodes



must be far enough from the mercury, and so protected by the shape of the vessel, that mercury cannot spatter on them, although they are continuously in an atmosphere of mercury vapor.

14. Connections. Fig. 8 shows simplified connections also. The anodes a and b are connected with terminals of an autotransformer; the cathode c is connected through a reactor with the positive terminal of a storage battery, and the start-

ing anode d, through a resistor with one of the autotransformer terminals. The negative terminal of the storage battery is connected with the middle terminal of the autotransformer, and two additional autotransformer terminals are connected with a single-phase circuit (A.-C. supply).

With alternating current in the autotransformer, an electromotive force exists between the anodes a b and d and the cathode c; a and b are alternately positive to c, and the polarity of anode d agrees with that of anode b. By tilting the vessel slightly, the two mercury pools join, and alternating current is

set up in the path e-f-resistor-g-d-mercury-c-reactor-storage battery-h, this current being limited by the resistance of the path. Righting the vessel opens the circuit by separating the two mercury pools and causes a spark at the separation. This spark starts the operation, current passing alternately from anodes a and b to cathode c, and thence through the reactor and the storage battery back to the autotransformer, always in the same direction through the battery or other direct-current device.

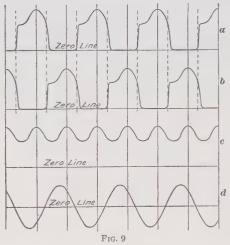
15. Theory.—Any conductor serving as a negative electrode, possesses, to some extent, an initial resistance that disappears as soon as current begins. Mercury, zinc, cadmium, and some other metals, especially the first mentioned, manifest this quality to a marked degree. This cathode resistance, which appears as an insulating film over the surface of mercury, is enormously increased in a vacuum. It is broken down completely by a hot spark or an arc, and remains absent while electricity is flowing to the mercury as the negative electrode, but forms again instantly when the current ceases. Without the aid of a starting spark, very high voltage, ranging from 6,000 to 25,000, would be required to break down this cathode resistance. Shaking the vessel so as to form ripples over the surface of the mercury assists high voltage to start current under such conditions.

After the current has started to the cathode, it must continue as long as operation is desired. The arc from one anode must begin before that from the other ends; otherwise, the cathode resistance will reestablish itself and the operation will cease entirely. The brief instant during which alternating current is passing through zero value is sufficient for this resistance to be reestablished. Means must therefore be provided for continuing the current from each anode during the instant of reversal until the other anode becomes positive. In practice, this provision consists of reactance in the direct-current circuit, either in the form of a special reactor coil, or as a property of the autotransformer. Enough energy is stored in the reactance to carry the arc past the zero point in the current wave. Fig. 8

indicates the use of special reactance, but the combination of this property in the autotransformer is very common.

16. Operation.—The nature of the current from a mercury rectifier will be more clearly understood on referring to Fig. 9. The current in one of the anodes is represented by the curves a, in the other by the curves b, the resultant rectified current through the direct-current circuit by curve c. Curve d represents the electromotive force impressed on the anodes.

The rectifier reverses alternate half waves of current, so that all half waves are in the same direction from the zero line



as shown at a and b. Fig. 9; also, the resultant direct current is not absolutely smooth, but of a wavy or fluctuating b nature, as shown in c: 'that is, it is a pulsating direct current. The extent of these waves can be modified by the use of more or less reactance in the direct-current cird cuit. For many uses, a pulsating direct current is not objectionable; for charging storage bat-

teries, such a current is thought to have some advantages. The effect of reactance can be seen in the peculiar shape of the curves a and b. On account of the storage of magnetic energy in the autotransformer core, the current does not rise at a uniform rate to full maximum value, as is shown by the depressions near the tops of the curves. During the latter part of each current wave, this stored energy maintains the current until the other anode becomes positive and begins to deliver current. The dotted lines indicate where the downward slope of each curve continues just past the beginning point of the preceding half wave from the other anode.

17. Phenomena During Operation.—While the rectifier is operating, a glow of light fills the bulb and a specially bright spot appears on the surface of the mercury. This spot continually changes its position, dancing around over the surface of the mercury, which is agitated as if boiling. Condensation of the mercury vapor, together with small drops of mercury thrown off by the agitated surface, forms globules on the glass. These globules gather in drops and run back to the pools in the bottom.

The total electromotive force drop in a rectifier bulb does not vary with the current, but depends largely on the length and the diameter of the vapor path and the number of bends, or angles, in this path. A constant drop of approximately 5 volts occurs at the anodes, and a little less at the cathodes; the drop through the vapor path varies from 4 to 5 volts up to possibly 15 volts. The drop in the mercury vapor increases when the vapor pressure is increased, and decreases when the temperature is increased. The presence of gases, other than mercury vapor, increases the drop very materially; hence, all other gases are excluded as completely as possible. In commercial low-voltage bulbs for battery charging, the total electromotive force drop is approximately 14 volts at any current, and in high-voltage bulbs for arc lighting, approximately 25 volts.

18. Current Capacity.—The current capacity of a bulb depends on the size of the leading-in conductors, especially the platinum wires sealed in the glass, and on the cooling capacity of the bulb. The voltage drop being fairly constant, heat is generated practically in proportion to the current, and, for good operation, the surface of the glass must be large enough to radiate this heat and prevent an excessive rise of temperature. The condensing mercury carries the heat to the glass, from which it escapes through radiation and convection. Immersion in oil hastens the dissipation of heat; this method is employed for arc-lighting rectifiers as will be explained later.

Theoretically, mercury rectifiers can be made for any desired current capacity, but in practice the difficulty of producing and maintaining high vacuums of large size has limited the current capacity to about 50 amperes. The extreme simplicity of the device and its low cost, compared with other rectifying



devices, make its further development attractive. The present difficulties will doubtless be finally overcome and the application of mercury rectifiers for converting alternating current to direct current will become very general.

19. Voltage.—The dimensions and the shape of the mercury path largely determine the direct-current voltage that a rectifier bulb can sustain and deliver. Fig. 8 and the discussion refer-

ring to it show that the electrodes serving as anodes are opposed to each other in polarity, and that if an arc should form across them, the autotransformer would be short-circuited. The forming of such an arc is prevented by the surface resistance of a negative electrode (see Art. 15) and by the length and shape of the vapor path. In practice, the anodes are so enclosed and protected that not a particle of mercury can spatter or fall

against them; otherwise, the negative electrode resistance would be broken down and a short circuit would result. Hence, the longer, narrower, and more crooked the vapor path, the higher will be the voltage that can be sustained.

20. Commercial Bulbs, or Tubes.—Fig. 10 shows a 5-ampere bulb for use on single-phase circuits. Standard rectifiers in which it is used are made for converting single-phase current at either 110 or

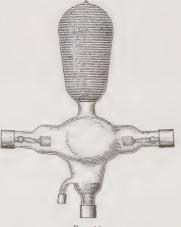
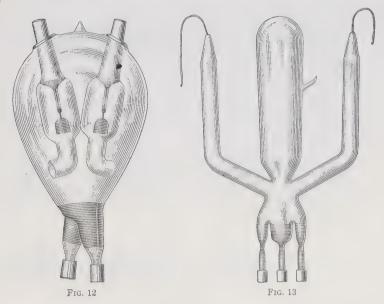


Fig. 11

220 volts into direct current at 16 volts, maximum; 10-ampere bulbs of similar appearance are also available. Fig. 11 shows

a 30-ampere bulb for converting 110- or 220-volt single-phase current into direct current at 120 volts, maximum; 50-ampere bulbs for the same service have the same general appearance. Figs. 12 and 13 show, respectively, a bulb and a tube (manufacturer's choice of terms) for high-voltage work in series-arc lighting.

21. Efficiency.—The efficiency of high-voltage bulbs is . higher than that of low-voltage bulbs, because the drop of voltage in the bulb is nearly constant and is therefore a smaller



percentage of the higher voltage. For example, when supplying a 14-volt battery circuit, the voltage drop in the bulb being 14, as before explained, the efficiency of the bulb cannot be over 50 per cent.; that is, the voltage loss in the bulb equals that supplied the circuit. If the voltage of the direct-current cir-

cuit is 134, the efficiency of the bulb is approximately $\frac{134}{134+14}$

= .905, or 90.5 per cent. On the other hand, the efficiency of a 3,500-volt bulb on a series-arc circuit is very high, the voltage

loss being less than 1 per cent. of the total direct-current voltage.

22. Rectifier bulbs, or tubes, are commonly used on single-phase circuits, and therefore have only two anodes; three anodes could be provided, however, and the bulb could be used on three-phase circuits. In this case, the direct current would be less pulsating because of six half-wave peaks instead of two on a single-phase circuit. Three-phase mercury rectifiers are very little used.

APPLICATIONS OF MERCURY RECTIFIERS

CHARGING STORAGE BATTERIES

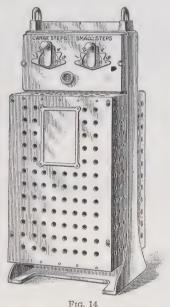
23. Mercury rectifiers are used to charge storage batteries, to operate arc lamps and moving-picture machines, for electrolytic work and electroplating, and in a few cases, for operating small direct-current motors. The chief uses are charging storage batteries and operating arc lamps.

Probably the largest field of application is to charge storage batteries. Batteries that can be economically charged by such rectifiers are those used for automobile motors and lights, motor boats, ignition for internal-combustion engines, telephone and telegraph service, signal and alarm systems, electric clocks, railroad car lighting, and chemical work. Among these several uses, charging automobile batteries is chief. This work in both public and private garages, employs many rectifiers.

24. Mercury rectifiers for battery charging are made non-automatic starting and automatic starting. The former requires attendance both at the initial start and to start again after stoppage due to overload, temporary voltage failure, or other cause. The automatic type starts again without attention after each failure until the charge is completed, when, if the conditions of the battery and the supply circuit are suitable, the operation ceases automatically. The automatic type is therefore superior where constant attendance is impracticable.

Commercial practice is to supply both types complete with rectifier bulb or tube and all necessary transformers, dial switches for adjusting the voltage, starting switch, circuitbreakers, fuses, etc. All the auxiliaries are compactly mounted and furnished with the necessary mechanical protection. The rectifier bulb is mounted upright in a pivoted holder arranged for tilting by hand or automatically, and for returning automatically to the upright position when released.

The dial switches afford a means of changing connections



§ 36



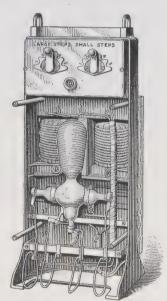


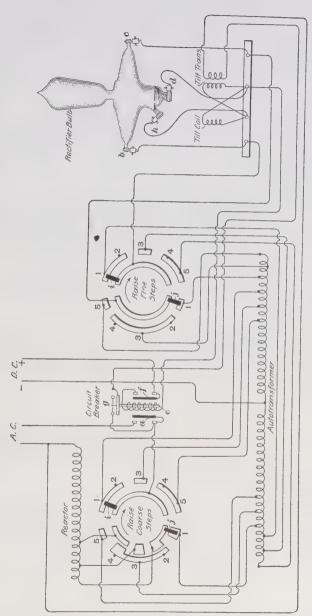
Fig. 15

with the transformers so as to raise or lower the direct-current voltage. This adjustment must be made approximately correct before operation can start. The correct adjustment depends on the number of cells to be charged in series, and to some extent, on their condition. If the battery is in good condition, the voltage at the beginning of the charge should be about 2.15 per cell, and at the end 2.55 per cell.

In starting the non-automatic type, the alternating-current and the direct-current circuits are closed, a hand-operated starting switch is moved by the operator to the starting position, and the bulb is tilted until the arc starts. The starting switch is then released, and it returns automatically to the running position. In some cases, the starting switch is so connected with the tilting mechanism that closing the switch in the starting position automatically tilts the bulb. While a non-automatic rectifier is operating, an attendant must be present.

- 25. Example of Mercury Rectifier for Battery Charging.—Figs. 14 and 15 show a 30-ampere mercury rectifier arranged for automatic starting; the handles of the two dial switches and the hand wheel for closing the circuit-breaker contacts are plainly shown in both views. This particular rectifier is typical of the product of one manufacturer only, but it will serve to illustrate all rectifiers for battery charging. It is automatic in that an electromagnet is arranged to tilt the bulb when the magnet is excited. This tilting mechanism is controlled by a relay on the back of the panel; the relay acts also as a circuit-breaker, opening both the alternating-current and direct-current circuits if the current in the latter becomes too high. Owing to the action of the tilting mechanism, this rectifier is automatically restarted if the arc goes out before a charge has been completed.
- 26. Fig. 16 shows the connections of this mercury rectifier. The two 5-point dial switches are so connected to the autotransformer and reactor taps as to give voltage adjustments to suit different numbers of cells. One dial adjusts the voltage in five coarse steps, and for each one of these steps the other dial gives five possible intermediate adjustments, making twenty-five total steps available.

One side of the alternating-current circuit is connected through circuit-breaker contacts a with a contact on the coarse-step switch, and the other side with the reactor, which, in, turn is connected with three contacts of the coarse-step switch. The autotransformer is provided with thirteen leads, six of which are connected with contacts on the coarse-step switch and six with contacts on the fine-step switch, the middle lead



Frg. 16

serving as the negative terminal of the direct-current circuit. The anodes b and c of the rectifier bulb are connected with the two main contacts on the fine-step switch; the cathode d is connected through the trip coil e of the circuit-breaker with one of the circuit-breaker contacts, which is joined through contact f with the positive terminal of the direct-current circuit. The primary coil of the small tilting transformer is connected between a contact g on the circuit-breaker and one side of the alternating-current circuit. The secondary coil is connected with points that serve as terminals of the two mercury electrodes d and h and also as terminals of the tilting coil.

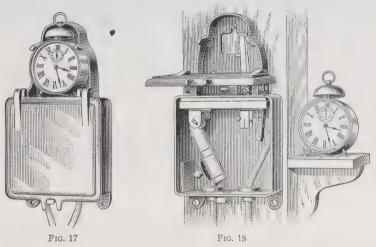
In Fig. 16 the plunger of the circuit-breaker is shown drawn down, a condition that prevails only when the rectifier is operating, that is, with current in the trip $\operatorname{coil} e$. At other times, a counterweight holds the plunger at the upper limit of its travel, closing the contacts g and placing the primary of the tilting transformer in series with the main circuit-breaker contact a.

The dial-switch stationary contacts are represented by sections of concentric rings, and the successive points of each switch are indicated by 1, 2, 3, etc. The moving contacts i and j are mounted under the ends of a lever pivoted at the center of the circles; these contacts connect adjacent stationary contacts of the two circles. Both dial switches are shown in position for the lowest voltage adjustment; rotating them clockwise raises the voltage, one by large steps and the other by small steps.

27. In operating the rectifier, it is started by adjusting the dial switches to give the desired voltage as nearly as possible; the circuit-breaker contacts a and f, Fig. 16, are then closed by turning the knob on the front of the rectifier case, and finally the line switch in the supply circuit is closed. Alternating current is thus set up in the path a-i-autotransformer-i-reactor, and also in the path a-g (which is closed until current is set up in e)-tilting transformer. Anodes b and c, being connected through the fine-step switch with the autotransformer winding, are thus subjected to alternating voltage, and the secondary voltage of the tilting transformer is applied between

the terminais of the tilting coil and between the mercury electrodes d and h. The resulting current through the tilting coil causes the bulb to tilt until the mercury electrodes join and short-circuit the tilting coil. The bulb then returns to the vertical position, breaking the mercury connection between the two lower electrodes and causing a spark.

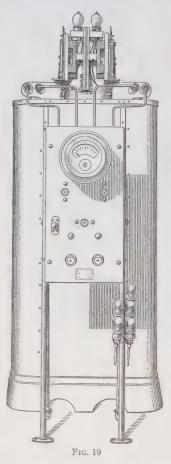
28. If the arc starts from either electrode b or c, Fig. 16, to the cathode d, direct current is established in the circuit, including coil e of the circuit-breaker, and the tilting-transformer circuit is automatically opened at contact g, thus stopping further tilting. If the arc does not start promptly, the



tilting continues until a correct start is made. While the rectifier is operating, too much current through the circuit-breaker coil draws the plunger down hard, trips a latch, and releases the breaker, thus giving overload protection. If the line voltage fails temporarily, or if the arc stops accidentally for any other reason before the current has fallen to less than 10 amperes, the circuit-breaker plunger rises promptly and closes contact g; the return of voltage then causes the bulb to tilt automatically and restore the arc.

If, however, the current falls gradually, the counterweight of the circuit-breaker plunger slips back slowly until its rod

is engaged by a latch, leaving contact g open and preventing further tilting. This feature is utilized in some cases to charge batteries during the night. The rectifier is adjusted for correct voltage at the beginning of the charge; as the battery volt-



age rises, the charging current decreases until it becomes so low that the arc goes out. This method of automatically terminating a charge can be depended on only when a battery is in good condition and the supply voltage is constant, conditions that seldom prevail in practice.

29. The automatic discontinuance of operation on gradual failure of current prevents repeated tilting after a charge has terminated. When the battery current falls to 5 or 6 amperes, the arc is no longer sustained, and were it not for the latch that automatically catches and holds the slowly rising circuit-breaker plunger, the bulb would continue to tilt until an attendant arrived and opened the breaker. This repeated tilting would be undesirable from a mechanical standpoint, even though the device might be safe, electrically, from injury.

A better plan to end operation

automatically, is by the use of a *time switch*. Figs. 17 and 18 show a form of such a device, which consists of a single-pole circuit-breaker in a cast-iron case and arranged to be tripped by an alarm clock. The alarm is set to go off at the time operation should cease, and the clock is pushed back into place.

When the alarm mechanism operates, it releases the circuitbreaker, which opens the circuit. The clock can be set to discontinue charge before it is fully completed, and an attendant can then supervise the completion in a comparatively short time.

OPERATING ARC LAMPS

30. Direct current is superior to alternating current for operating some types of arc lamps, especially those of the metallic-flame type, while alternating current has advantages even more striking for transmitting and distributing energy.

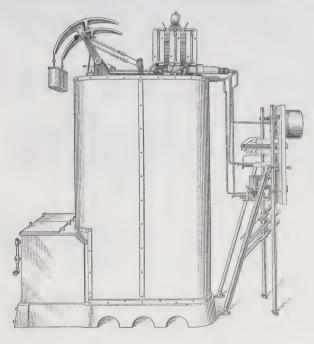


Fig. 20

The mercury rectifier operating in conjunction with a constant-current regulating transformer offers a ready means of gaining the advantages of both alternating-current distribution and direct-current arc lamps.

As the essential parts and the main features of operation of rectifiers for series-arc circuits are the same, a description of one make will give a good idea of the construction and operation of all. Fig. 19 shows the front of a combined unit, series mercury-arc rectifier set consisting of a constant-current transformer, a direct-current reactor, a tube tank, and an exciting transformer mounted on one base with the switchboard in the foreground, and Fig. 20 shows a side view of this device.

31. Rectifier Outfit for Arc Lighting.—The constant-current transformer shown in Figs. 19 and 20 is of the air-cooled type. Its core and coils appear as shown in Fig. 21, and its assembly, as shown in Fig. 22. The method of counter-

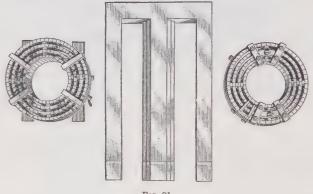
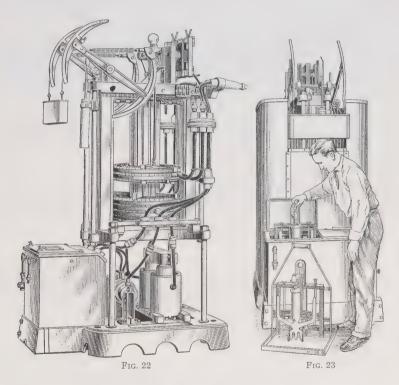


Fig. 21

balancing the primary coils is such that their distance from the fixed secondary coils changes automatically with each change of secondary current. This movement adjusts the magnetism through the secondary coil so as to keep the secondary current nearly constant.

The tubes are in carriers submerged in oil in a separate tank adjacent to the transformer tank. This oil is kept cool by circulating water through coils of pipe inside the tank. The tubes are easily removed, as shown in Fig. 23. Rectifier outfits are also made for arc lighting, in which the transformer coils and the bulbs are oil-immersed in one tank, the oil being cooled by circulating water in coils of pipe.

32. An indicating lamp in series with each tube or bulb on or near the rectifier outfit informs the operator whether the tube is operating. Reactors in each circuit smooth out current pulsations; static dischargers and lightning arresters with each outfit protect from injury by heavy electrical stresses. Exciter transformers furnish low-voltage current to start the arc. A magnet controlled by a hand-operated switch is provided for shaking or rocking the tube without opening the case.



The indicating lamps and static dischargers are mounted on top of the transformer, as is shown in Figs. 19, 20, and 22. The exciting transformers and reactances are mounted under the main transformers, as in Fig. 22.

Series mercury-arc outfits are made for 4- and 6.6-ampere circuits with twenty-five, fifty, and seventy-five lamps in series.

The outfit just described is for a 50-lamp circuit, the two tubes operating in series. Single outfits are also in use with two bulbs, each supplying a separate and distinct fifty-lamp circuit.

OPERATING MOVING-PICTURE MACHINES

33. Mercury rectifiers are especially successful in supplying direct current for operating moving-picture machines. The direct-current arc gives clearer, whiter, steadier, and stronger light on the screen than can be obtained with equivalent energy in the form of alternating current. If direct-current lighting circuits are available, they are usually at voltages much higher than are needed for the moving-picture machine, necessitating much loss in regulating resistance. Lighting circuits, however, usually carry alternating current, and by means of the mercury-arc rectifier the advantages of the direct-current arc can be obtained without excessive loss, the current being regulated by means of transformers and choke coils.

ALTERNATING-CURRENT MO-TORS AND SYNCHRONOUS CONVERTERS

POLYPHASE INDUCTION MOTORS

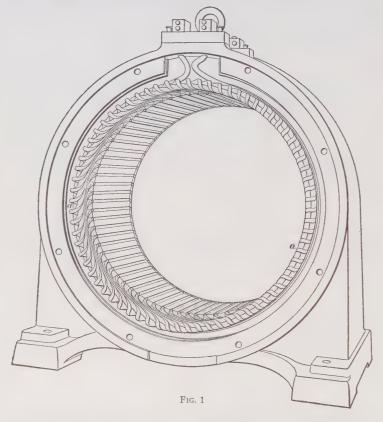
ESSENTIAL MEMBERS

- 1. Rotative devices driven by alternating-current energy are *induction motors*, *synchronous motors*, and *synchronous converters*, each of which has its field of usefulness.
- 2. Because of its simplicity, economy, and durability, the induction motor is far more commonly used than any other type of motor for industrial purposes. An induction motor consists of two essential members, the *primary*, which is connected to the electrical circuit, and the *secondary* in which electric currents are induced by the magnetic flux produced by the primary currents. Generally, though not necessarily, the primary is stationary and receives electrical energy, which is transformed into mechanical energy in the rotor or secondary.

Other names commonly applied to the primary are stator and field, and to the secondary rotor and armature. Primary and secondary usually relate to electrical performance, and the other terms to mechanical features. In this Section the terms primary and secondary are generally used, as they more clearly describe the electrical functions of these parts. Induction motors are made for operation on polyphase and single-phase circuits.

POLYPHASE MOTOR PRIMARIES

3. Construction.—The primary, or *field*, of an induction motor is practically the same in construction as that of the stationary armature of an alternator. Induction motors, however, are generally smaller than alternators. Fig. 1 shows the general appearance of the primary for a polyphase motor.



A laminated core with slots in the inner face is clamped between plates held together by rivets, bolts, keys, or other means, according to the design. The core may be assembled in a frame, as in the illustration, or it may be provided simply with supporting feet attached to the clamping rings, or end shields, as in Fig. 2, the central part of the core being exposed. The core punchings are here shown assembled in bunches and shaped to present more cooling surface to the air.

Coils a, Fig. 1, are assembled in slots, which are usually open at the top, with notches for wedges, as explained in connection with alternators. In such cases, the coils are held in place by wooden or metal wedges. Some induction-motor primaries are made with slots partly closed at the top, and, in assembling, the coils are passed through the narrow openings.

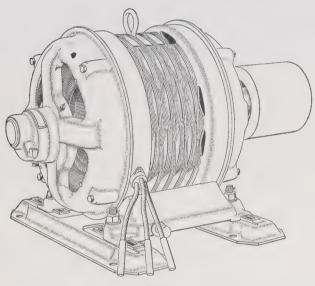
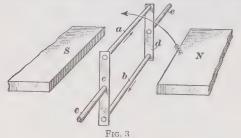


Fig. 2

4. Rotating Magnetic Field.—The rotative effort, or torque, of every induction motor depends on the fact that magnetic poles caused by the alternating currents in the primary windings revolve about the center, giving the effect of a rotating magnetic field, or flux; that is, the torque is caused by the rotating flux. If the field frame of a direct-current motor were rotated with the field excited, the flux in sweeping over the armature conductors would induce electromotive forces in them. If the brushes were lifted from the commutator

and all the bars short-circuited by a metal ring, currents would be established in the armature conductors, and the reaction between these currents and the magnetic flux would cause the armature to rotate in the same direction as the field frame. Exactly the same effect occurs in an induction motor, but without any movement of the primary coils or core, simply a revolution of magnetic flux.

Fig. 3 illustrates the principle of the rotating flux. Conductors a and b short-circuited by end pieces c and d represent one element of an induction motor of which e e represents the shaft and N and S two magnetic poles revolving in the direction indicated by the long arrow. These poles do not represent a revolving part of the machine, but simply revolving north and south magnetic poles. Currents are induced in the conductors



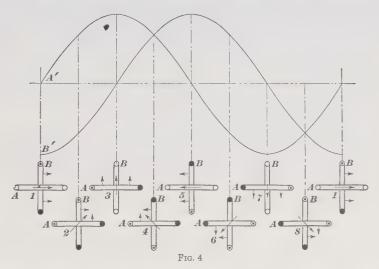
in the directions indicated by the short arrows, and these currents induce a south pole on the face of the loop $a\ d\ b\ c$, adjacent to the revolving north magnetic pole and a north pole adjacent to

the revolving south pole. The motor element is thus drawn around by magnetic attraction of the revolving poles.

5. Theory of Rotating Field.—The theory of the rotating field, or revolving magnetic flux, of an induction motor will be more clearly understood by reference to Fig. 4, in which A and B represent two closed coils at right angles to each other, and curves A' and B', two-phase currents. It should be understood that the currents in the coils vary as represented by the curves, giving varying conditions of polarity in the two coils, as indicated at positions 1, 2, 3, etc. The coils do not move; the different positions merely indicate different current and polarity conditions.

At position 1, the current in coil A is 0 and that in coil B maximum negative, as shown by the curves A' and B'. The

polarity of the coil B is indicated by short arrows, and the resulting polarity of the two coils, by the longer arrow; in this case, the arrows agree in direction, because coil A carries no current. In position \mathcal{Z} , each coil is carrying the same current, that in A being positive and that in B negative, as shown by the curves. The resulting polarity, as indicated by the longer arrow, is now 45° counter-clockwise from the first position. In position \mathcal{Z} , the current in A is maximum positive and that in B, $\mathbf{0}$, the resulting polarity is 45° farther counter-clockwise. The remaining positions show that as the current continues its cycle of changes the resulting polarity of the two coils



continues to rotate counter-clockwise and that one rotation is completed per cycle. Either two-phase or three-phase currents in suitable windings on an induction-motor primary causes a rotating magnetic field, according to this principle.

If the connections of one phase are reversed, the direction of rotation is reversed. For example, if the current in coil B were reversed, curve B' would be maximum positive when A' is θ and θ when A' is maximum positive, and so on. The polarity of winding B would then be reversed in every case, and the resulting polarity of the two windings would rotate clockwise.

6. Synchronous Speed.—The primary windings of an induction motor are arranged and connected for a given number of pairs of poles, as explained in connection with alternators. Any magnetic pole makes one complete revolution in the field structure in as many cycles as there are pairs of poles. If f represents the frequency, in cycles per second, and n the number of pairs of poles, the number of revolutions of the magnetic poles per second is $f \div n$ and the revolutions per minute, or synchronous speed, is $\frac{60 f}{n}$

When the speed of a motor is in accordance with this formula, the motor speed is said to be synchronous with that of the alternator, or the motor and alternator are said to run in synchronism.

7. Slip.—The flux of the magnetic poles cuts across the secondary conductors and induces in them the current that causes the secondary to rotate. If the secondary were rotated at synchronous speed, its conductors would not cut the flux and no turning effort, or torque, would be exerted. The secondary therefore rotates at enough less than synchronous speed to allow the required current to be induced in its conductors. The difference between synchronous speed and the speed of the secondary is called the slip of the motor. Slip is nearly always expressed in per cent. of synchronous speed. Thus, according to Art. 6, the synchronous speed of a four-pole sixty-cycle induction motor is $\frac{60 f}{n} = \frac{60 \times 60}{2} = 1,800$ revolutions per minute; if the speed of the motor secondary is 1,710 revolutions per minute, the slip is $\frac{1,800-1,710}{1,800} \times 100 = 5$ per cent. The full-load slip of commercial induction motors for general

The full-load slip of commercial induction motors for general service ranges from possibly 8 per cent. in small motors to 2 per cent. in motors of 100 horsepower and larger.

8. Variation of Slip With Torque.—The torque must be great enough to make the secondary rotate. As the torque depends on the current in the secondary conductors, and this

current depends on the rate of cutting lines of force, the slip while the motor is running, automatically adjusts itself according to the torque required. If the load increases, necessitating greater torque, the slip increases accordingly; if the load decreases, the slip decreases. The slip at no load, that is, with the motor running idle, is very low, the speed of the secondary being very nearly synchronous.

- 9. Effect of Secondary Impedance on Slip.—The induced currents in the secondary conductors vary directly with the electromotive forces induced in the conductors and inversely with the impedance of the conductors and their interconnections. As the secondary curren'ts must be enough to cause the required torque, the induced electromotive forces must be greater in a secondary having high impedance than in one with low impedance; that is, the slip depends also on the secondary impedance.
- 10. Direction of Rotation.—The direction of rotation of an induction motor agrees with the direction of rotation of its magnetic field, and can be reversed by interchanging the connections of one phase of the primary.

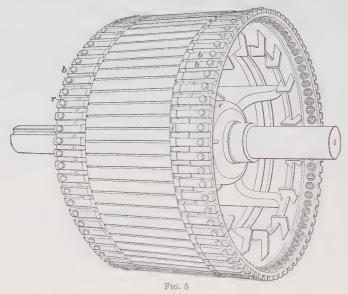
POLYPHASE MOTOR SECONDARIES

SQUIRREL-CAGE ROTORS

11. Induction-motor secondaries, or rotors, are of the squirrel-cage type and the coil-wound, or phase-wound type, either of which can be used in the same primary. The motors are designated, according to the type of rotor used, as squirrel-cage motors, and phase-wound motors.

Fig. 3 shows an element of a squirrel-cage rotor, straight bar or rod conductors short-circuited at the ends. Fig. 5 shows a complete squirrel-cage rotor, in which the conductors b are bolted to end rings r. The conductors and end rings have the general form of a squirrel-cage wheel, which fact gives the rotor its name. As its resistance is not adjustable, it might also be called a *constant-resistance rotor*.

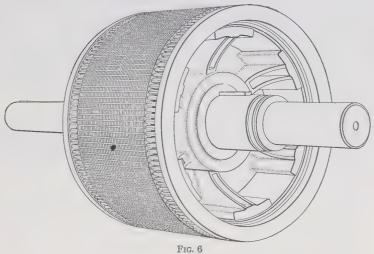
12. Construction.—The construction of a squirrel-cage rotor is very simple. A laminated iron core is assembled on a cast-iron spider, which is pressed on a shaft and keyed. In some cases, especially with small motors, the core is assembled and keyed directly on the shaft, the spider being omitted. The core is clamped between end plates secured to the spider or to the shaft, and is provided with slots in the outer periphery. Straight copper bars or rods are placed in these slots, and the ends of the bars are fastened to rings. The bars are usually



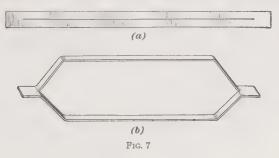
not insulated from the iron, because most of the current follows the bar rather than the higher resistance laminations. In some cases, a piece of thin paper is wrapped around each bar, as at i, Fig. 5; insulating cement is sometimes used instead of paper, making the rotors impervious to moisture and capable of withstanding great heat.

13. Among the methods used to fasten the bars to the end rings are bolts, bolts and solder or solder alone, keystone construction, welding, cast-on end rings, and closed-coil construction. The high temperatures at the rings are liable to

loosen bolts and solder, especially in heavy service. In the keystone construction, the conductors are thrust through holes in edgewise end rings (planes perpendicular to the shaft) and



then keyed in place. Welding the bars to the rings makes very durable construction, as does also casting solid rings on the ends of the bars, as in Fig. 6. Closed coils are sometimes installed instead of the strictly squirrel-cage construction, and



with these coils no end rings are necessary. Copper strips are slit lengthwise through the center, except a small part at each end, as in Fig. 7 (a), and the sides are drawn apart as in (b).

14. Starting Squirrel-Cage Motors.—When an induction motor is first connected with a source of alternating current, and before the secondary begins to rotate, the slip is 100 per cent.; the momentary current taken from the line would be several times full-load current unless some means were taken to limit the starting current. Squirrel-cage induction motors up to and including 5 horsepower are usually started by switching them directly on to the line, but larger sizes are provided with some form of starting device. This device may be a resistance starter or an autotransformer starter.

15. Resistance starters are recommended by some manufacturers for polyphase induction motors of from 5 to 25

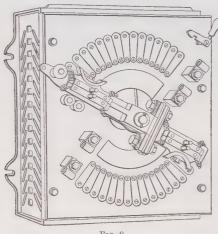


Fig. 8

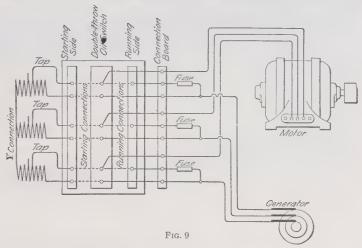
or 30 horsepower. They consist of non-inductive resistances arranged for connection in two phases of the primary circuit and for being cut out in steps as the motor speed accelerates, very much the same as operating a direct-current motor starter. This resistance limits the starting current to a safe value until the motor speed accelerates and reduces the slip. Fig. 8

shows a typical resistance starter for induction motors. The same type of starter can be used for either a two-phase or a three-phase motor, although the resistances are different. The use of only two resistances in starting a three-phase motor slightly unbalances the phases, but not enough to cause difficulty with the size of motors using such starters. Automatic low-voltage release devices are frequently employed on these starters.

16. Autotransformer starters, variously called autostarters and compensators, consist of autotransformers with

switching devices so arranged that reduced voltage can be impressed on the motor primary for starting. By the principle of the autotransformer, the current in the motor primary is increased over the current taken from the line in approximately the same ratio as the starting voltage is decreased from the line voltage. This fact gives the autotransformer starter a possible advantage over the resistance starter, since with the latter the line current and the motor current are the same.

17. Fig. 9 shows the connections of a starting compensator with a three-phase squirrel-cage induction motor. The



double-throw switch with contacts immersed in oil can be moved from its off-position first to the starting position and then to the running position.

In the off-position, both autotransformer and motor windings are disconnected from the line. In the starting position, the switch connects the line to the ends of the autotransformer winding and the motor to the taps, without breakers, or fuses, in circuit. In the running position, the autotransformer winding is cut out and the motor is connected to the line through fuses or overload relays. To prevent the attendant from throwing the motor directly on the line, thereby causing a rush of current, which the autotransformer is designed to avoid,

an automatic latch is provided. This latch is so arranged that the lever can not be thrown from the off-position directly into the running position; it must first be moved into the starting position (backward) and from there into the running position (forward) by a quick throw of the lever, thereby avoiding any appreciable drop in speed and consequent increase in current in passing from the starting into the running position. If moved too slowly from the starting to the running position, the lever is automatically caught and held in the off-position.

18. Three autotransformer taps are generally provided in each starter, and after a motor is installed the tap that will give best results should be selected. The taps are generally so placed that one will give from 40 to 50 per cent. of line voltage on the motor, another from 60 to 65 per cent., and the third about 80 per cent. The lowest voltage will answer where the motor starts freely; the middle tap serves in the great majority of cases, while the highest starting voltage is useful only when the motor must start with high torque, as in starting a long line shaft or a machine with heavy rotating parts.

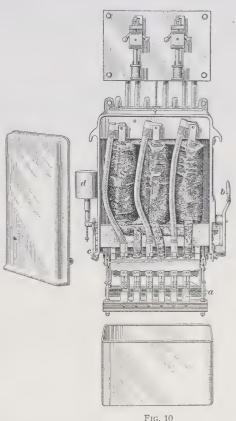
The motor should start its load promptly and accelerate to full speed in not more than 1 minute after the switch is closed in the starting position. If a tap giving too low starting voltage is selected, the starting period will be too long, especially with frequent starting, and the autotransformers may be overheated. On the other hand, if the starting voltage is too high, the starting current will be higher than is necessary; the motor will start with a violent jerk and accelerate very rapidly. In any case, the switch should be left in starting position until the motor attains very nearly full speed and should then be thrown quickly to the running position; if this change is made too soon, an unnecessary rush of current is caused when the change is made, and if delayed too long the autotransformers may be overheated.

19. Autotransformer starters are usually provided with springs, latches, and magnets that automatically return the contacts to the off-position if the voltage fails while the motor is operating. The return of voltage cannot then cause an

injurious rush of current. Overload protection is also good practice; it is usually installed in the form of fuses or circuitbreakers. Fig. 9 shows a fuse in each running lead, but none in the starting leads. The starting current is of such short duration that it rarely works injury. The same fuses cannot

be used to carry both starting and running current, because, if the fuses were large enough to carry the starting current they would be too large to afford protection from a continuous over-load that might injure the motor while running.

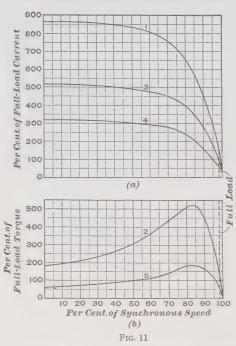
Fig. 10 shows a starting compensator partly dissembled. The oil tank is lowered to show the switch contacts a. These are operated under oil by means of the handle b. The operating shaft extends through, and is connected by, levers c with the low-voltage device d, which releases a latch and allows the contacts to



return to the off-position on failure of voltage while the motor is operating. Overload relays, or circuit-breakers, mounted on a panel above the compensator open and protect the motor from injury that might be caused by excessive loads. Autotransformer starters are used with squirrel-cage induction motors of all sizes.

20. Starting Current and Torque.—Fig. 11 shows typical current and torque conditions in starting a squirrel-cage motor. Abscissas represent per cent. of synchronous speed, and ordinates represent per cent. of full-load current on curves in (a) and per cent. of full-load torque on curves in (b).

Curve 1 shows the starting current with full line voltage. At the instant the line switch is closed the current is 875 per



cent. of full-load current, or nearly nine times. As the speed increases this current decreases, at first gradually and then more and more rapidly. Curve 2 shows the torque exerted by the motor when starting on full voltage; it is about 175 per cent. of full-load torque at the start, increases to more than five times full-load torque at about 85 per cent. of synchronous speed. and then falls to full load value at about 98 per cent. of synchronous speed.

Curve 3 shows the motor current while starting with an autotransformer connected for 60 per cent. of line voltage in the starting position; curve 4 shows the corresponding line current, and curve 5, the torque. The starting current in the motor is 525 per cent. of the full-load current, and the line current only 320 per cent., or approximately 60 per cent. of the motor current. The torque, curve δ , is about 60 per cent. of full-load torque at the start, increases to nearly 200 per cent.

at 85 per cent. of synchronous speed, and falls to 100 per cent. at full-load speed. In this case, full-load speed is 98 per cent. of synchronous speed; that is, the slip is 2 per cent. The current curves do not decrease to zero at synchronous speed because of the magnetizing current, which causes the rotating field.

21. The torque of an induction motor varies as the square of the voltage impressed on the primary.

Let T= torque at full line voltage; $T_1=$ torque at reduced voltage; $E_1=$ full line voltage; $E_1=$ reduced voltage. Then, $T_1=\frac{E_1^2}{T}=\frac{E_1^2}{E^2}$, or $T_1=T\frac{E_1^2}{E^2}$; (1) also, $E_1=E\sqrt{\frac{T_1}{T}}$ (2)

When the full-load torque is known, the torque at any reduced voltage may be readily determined by applying formula 1. For example, if the voltage falls from 110 normal 100° the reduced torque is 100° 100° 20° at 22° cm 22° cm

to 100, the reduced torque is $\frac{100^2}{110^2} = \frac{100}{121} = .826$, or 82.6 per cent.

of the full-load torque; in other words, a reduction of 9 per cent. in voltage reduces the torque 17.4 per cent., provided the current remains constant. If the motor load remains constant, however, the current input increases enough to give the required torque unless this torque is beyond the motor capacity, in which case the motor stops. The line voltage should therefore be kept very nearly constant, because at low voltage the motor may either stop or become overheated.

By means of formula 2 the starting voltage for any torque within the capacity of a motor can be predetermined, provided the torque of the motor at full voltage is known. For example, if a motor will start at full line voltage with 2.75 times full-load torque and only full-load torque is needed, the starting voltage should be

 $E_1 = E\sqrt{\frac{1}{2.75}} = E\sqrt{.364} = .6 E$, approximately.

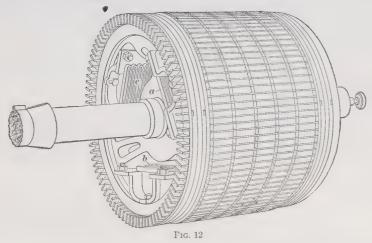
With a standard starter, an autotransformer tap giving 60 or 65 per cent. of full voltage for starting would be satisfactory in this case. Many induction motors are made for general service to give from 2 to 3 times full-load torque with full line voltage.

PHASE-WOUND ROTORS

- 22. The secondary windings of an induction motor may also consist of coils, each spanning approximately the same are as a primary coil and all connected so that the resistance of the secondary circuit can be varied at will. The names phase wound and variable resistance apply to such secondary construction. Increasing the resistance in the secondary circuit of an induction motor reduces the starting current for a given torque; it also reduces the speed, when the motor is operating, in much the same manner as does resistance in circuit with the armature of a direct-current motor.
- 23. Application.—Induction motors with phase-wound secondaries are used in preference to squirrel-cage induction motors where high starting current is objectionable and where speed regulation is necessary. The high starting current taken by squirrel-cage motors disturbs the line voltage and is objectionable where: (1) motors and lights receive energy through the same circuit, (2) the feeders, or conductors, leading to the motors are small, and (3) a motor is large enough to take a considerable part of the output of the generator supplying it.
- 24. Under case 1, the brilliancy of the lights is decreased every time the motor starts. To avoid affecting the lights, separate circuits are frequently installed for power and lights. Under case 2, if the feeders are small, the voltage at the motor may drop considerably with high starting current and heavy overloads, and since the torque decreases with the square of the voltage, difficulty may be experienced in starting and in carrying overloads. Under case 3, high starting current will seriously affect the regulation of the generator, causing reduced voltage at the generator terminals and thus affecting the whole

system. For these reasons, many central stations insist that induction motors above a specified capacity must have phase-wound secondaries.

25. Construction.—The mechanical construction of a phase-wound secondary is essentially the same as that of a squirrel-cage secondary, but the electrical part, that is, the windings and connections, differ. The coils of the phase-wound secondary are practically always connected in three-phase star for use in both two-phase and three-phase primaries; the free end of each phase is arranged for connecting resistance in series. This resistance may be *internal* or *external* to the secondary.



26. Internal-resistance secondaries are applicable in some cases where the starting requirements are only a little too severe for squirrel-cage motors. The resistors are mounted on the rotor spider in the manner shown at a, b, and c, Fig. 12, and are cut in and out of the rotor circuit by moving an inside contact by means of a spindle in the center of the shaft with a knob at the outer end. This knob is shown at the extreme right; withdrawing it places the starting resistance in circuit, and pushing it in short-circuits the secondary winding. Such resistance is used for starting only, not for speed regulation.

27. Fig. 13 shows a complete induction motor of the internal-secondary-resistance type with a pulley for belt drive. In order to start the motor, the knob at the left is pulled to the outward limit of its travel and the line switch (not shown) is closed, placing full voltage on the motor primary with all resistance in the secondary circuit; after the motor has started, the knob is gradually pushed in as the speed accelerates. When the motor is up to speed and all the resistance is cut out, it operates with the same characteristics as a squirrel-cage

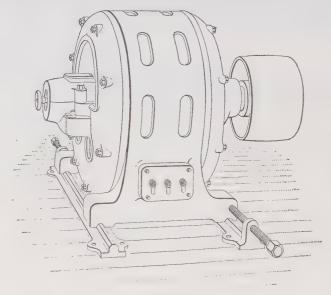


Fig. 13

motor. Applications of such internal-resistance motors are confined to constant-speed service, where low starting current is desired.

28. External-resistance secondaries are used in induction motors for starting conditions that are more severe than can be met satisfactorily with any other type of secondary and for service where speed regulation is required. The terminals of the star-connected winding are connected with collector rings on the shaft, and stationary brushes sliding on

these rings furnish a means for connecting external resistance in the secondary circuit. These *slip-ring motors*, as they are called, are much more widely used than those of the internal-resistance type.

29. Starters for slip-ring motors consist essentially of three resistors, with switching devices to adjust the connections so as to vary the amount of resistance in the secondary circuit. Fig. 14 shows typical conditions; a, b, and c represent the three phases of the secondary, r_1 , r_2 , and r_3 the three resistors, and d represents the switching device. This switch is

indicated in the off-position, all resistance being in circuit; turning it clockwise, as indicated by the arrow, cuts the resistance out of circuit in steps. The switching device may be of the face-plate type, as indicated, or of the drum type. The drums are the same in principle as those already shown in connection with direct-current motors.

30. Starting Characteristics of Phase-Wound Motors.—Fig. 15 shows the current and torque changes

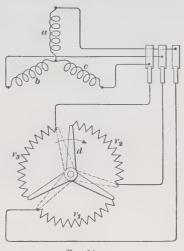


Fig. 14

while starting with three sections of resistance; the curves in (a) show current changes and the curves in (b) torque changes. Curves a and a_1 show current and torque with all the starting resistance in circuit; curves b and b_1 , the same conditions with one section of resistance cut out; curves c and c_1 , with two sections out; and curves d and d_1 , with all the starting resistance out of circuit. The heavy zigzag lines e and e_1 show current and torque changes as the starting resistance is cut out of circuit in steps.

According to curves a and a_1 , the motor starts with 150 per cent. of both full-load current and full-load torque. Both

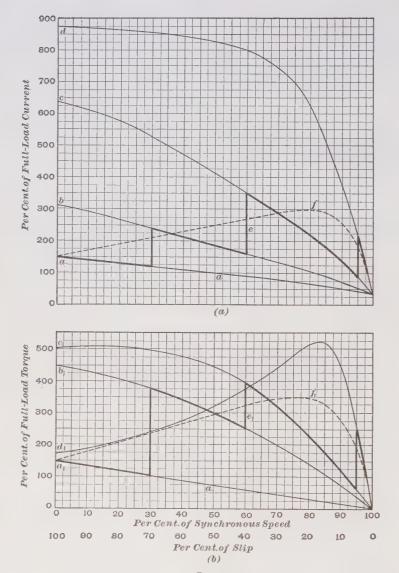


Fig. 15

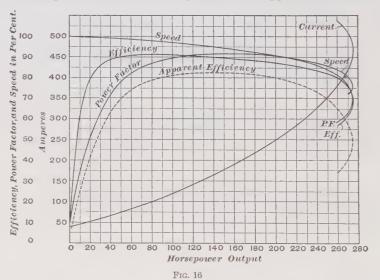
decrease as the motor speed increases until the first section of resistance is cut out, when the current increases to 240 per cent., a point on curve b, and the torque to 375 per cent., a point on curve b_1 . When the second and third sections of resistance are cut out, other increases of both current and torque occur, causing increased speed; in each case the values decrease as the speed increases until the motor is operating at full speed, 98 per cent. of synchronous speed (2 per cent. slip), with both current and torque at 100 per cent., or full value. If the starting resistance were cut out in very small steps, the current and torque would change more nearly as shown by the dotted curves f and f_1 . The magnetizing current for the rotating field causes the current curves to end above the zero line at synchronous speed.

PERFORMANCE AND SPEED CONTROL

- 31. Characteristic Curves.—The curves in Fig. 16 show performance characteristics (speed, efficiency, power factor, and current) of a 100-horsepower, sixty-cycle, 440-volt, three-phase squirrel-cage induction motor. Let it be assumed that the motor is running idle; then, increasing the load causes the speed to decrease to 96.5 per cent. at full load (slip 3.5 per cent.); at the same time, the current increases to 120 amperes at full load. The efficiency reaches maximum, slightly more than 91 per cent., at 80 horsepower and remains above 90 per cent. until the load exceeds 125 horsepower. The power factor reaches 89 per cent. at full load and continues to rise until the load reaches 160 horsepower—a load greater than can be safely carried by such a motor for more than a very brief period.
- 32. Pull-Out Torque.—If the load of an induction motor is increased indefinitely, a point will finally he reached where the motor will pull out of step and stop. The torque required at this point is called the pull-out torque. The limit of the momentary overload capacity of the motor is reached when developing torque just below the pull-out torque. The motor for which curves are shown in Fig. 16 has a pull-out torque about two and one-half times full-load torque; after the load

has passed this point, the current increases very rapidly and all the other characteristics decrease, as shown by the sharp bends at the ends of the curves. In a line of motors for general service, the pull-out torques usually range from one and one-half to three times full-load torque. These maximum torques are of use only in starting or for very intermittent service, because they are far beyond the continuous capacities of the motors.

33. Apparent Efficiency.—The product of the efficiency and the power factor divided by 100 is the apparent efficiency.



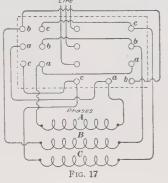
For example, the full-load efficiency, as shown by the curve in Fig. 16, is 91 per cent. and the full-load power factor 89 per cent.; the apparent efficiency is $91\times89\div100=81$ per cent., nearly, as shown by the broken-line curve. Multiplying by 100 the ratio of the output to the apparent input also gives the apparent efficiency.

34. Speed Control by External Resistance.—Although an induction motor tends to run in synchronism with the alternator supplying it with current, it never quite reaches

synchronous speed, because some energy is necessary to overcome friction, windage, copper losses, and magnetic losses. even when the motor is running idle. Nor can the speed rise above synchronism, but, with the exception of the slight variations due to the changes in load and corresponding change in slip, the speed remains practically constant as long as the speed of the alternator and voltage on the line remain constant. Generally, the induction motor is not so well adapted for variable speed as the direct-current motor, although its speed can be varied through a considerable range. The speed of an externalresistance induction motor may be reduced by increasing the amount of resistance in the secondary circuit. When

this resistance is large, the slip also must be large to induce enough current to provide the requisite torque: consequently, the greater the resistance the lower will be the speed.

The connections are the same as when starting with external resistance, Fig. 14, but the resistors and switching devices are heavier, because they must carry the secondary currents longer than for

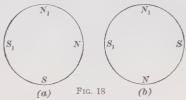


starting. This method of speed control is used for phasewound induction motors in heavy, varying-speed service, such as on hoists and cranes.

The speed characteristics of an induction motor with control resistances in the secondary circuit are very similar to those of a direct-current motor with control resistance in the armature circuit; that is, the speed varies inversely with the load. Such motors are therefore not suitable for applications in which constant speed with varying load is required at each speed adjustment.

Multispeed Motors.—If only a few speed changes are required, they can be made by changing the number of primary For example, six leads from a three-phase primary

can be brought to a multipoint switch, as in Fig. 17; closing this switch to the right connects the primary phases in star. and closing it to the left connects them in delta. The windings are so arranged that with star connections adjacent poles have the same polarity, as in Fig. 18 (a), and with delta connections adjacent poles have unlike polarity, as in (b). Adjacent poles N and N_1 in (a) combine to form one pole and S and S_1 to form another, while in (b) each pole remains distinct, thus giving twice as many poles in the latter case as in the former. Since the speed varies inversely as the number of poles (Art. 6), closing the switch to the right gives double the speed obtained on closing it to the left. On a twenty-five-cycle circuit, for example, a two-pole primary gives 1,500 revolutions per minute, synchronous speed, and a four-pole primary 750 revolutions per minute.



Two windings can be placed on the primary similar to the one just described and arranged for connection by means of a drum-type switch to form four numbers of poles

giving four speeds. The ratios in four-speed motors are usually 1, $\frac{2}{3}$, $\frac{1}{2}$, and $\frac{1}{3}$. For example, on sixty-cycle circuits, 4, 6, 8, and 12 poles give synchronous speeds of 1,800, 1,200, 900, and 600, and on twenty-five-cycle circuits the same numbers of poles give synchronous speeds of 750, 500, 375, and 250.

36. If designed for constant torque at all speeds, the horse-power of a multispeed motor varies with the speed. Even under this condition, a two-speed motor must be from 30 to 40 per cent. larger than a single-speed motor for the same torque at the highest speed, and the size of a four-speed motor must be increased from 70 to 80 per cent. If constant horsepower output is required at all speeds, a two-speed motor must be about 100 per cent. larger, and a four-speed motor about 150 per cent. larger, than a motor for the same output at the highest speed only. These figures are based on continuous operation at any of the speeds; for intermittent operation at

reduced speeds, the percentages might be different, depending on the service conditions. Increased weight and cost and complicated connections and switching arrangements are objections to multispeed motors; these objections limit their general application.

INDUCTION GENERATORS

37. If the primary of an induction motor is connected with an alternating-current circuit and the machine is driven by some external power at a speed higher than synchronism with the alternating current, the machine becomes an induction generator and supplies energy to the circuit; that is, this generator operates in parallel with the alternator from which it receives its magnetizing current.

Induction generators can be operated only in parallel with one or more alternators. The alternator fixes the speed above which the induction generator must be driven and furnishes the magnetizing current for the rotating field of the generator. This magnetizing current, being 90 electrical time-degrees behind the power current, reduces the power factor of the system, necessitating increased field excitation of the alternators. For example, if the power current in the primary winding of an induction generator is 100 amperes and the exciting current is 25 amperes, the total current is $\sqrt{100^2+25^2}=103.1$ amperes and the power factor of the system is $\frac{100}{103.1}=.97$, or 97 per

cent., of what it would be without the induction generator.

Induction generators with squirrel-cage secondaries are the only ones in commercial use. They are of simpler construction than alternators, have no sliding contacts, and are lower in cost; but the mechanical clearance in the air gap is small and the effect on the power factor undesirable. Where induction motors are used on electric railways, this generator action, when driven above synchronism, is of some advantage for regenerative braking on down grades. The use of induction generators otherwise is somewhat limited, but would probably be more general if their advantages were better known.

SINGLE-PHASE MOTORS

DESCRIPTION AND CLASSIFICATION

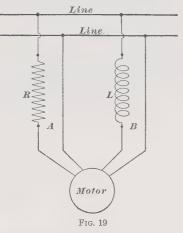
- 38. The single-phase induction motor is essentially the same in construction as the polyphase motor, the principal difference being in the method of starting and the way in which the revolving flux is set up after the motor is running at operating speed. If an induction-motor primary is provided with only one winding and is connected with a single-phase circuit when the secondary is at rest, the magnetic poles in the primary core do not rotate, but simply reverse. Their location remains constant, and no torque tending to start a squirrel-cage rotor is developed. But if such a rotor is started in either direction, it will accelerate in that direction to a speed very nearly in synchronism with the primary current and continue to run as a single-phase induction motor.
- 39. The most simple explanation of these facts is that the resultant effects of the primary current and the induced current in the moving secondary establish a rotating magnetic field. At standstill, the magnetic field is stationary; as the speed increases, the flux rotation becomes more nearly like that of the polyphase motor, until at operating speed it is practically identical. A two-phase or three-phase motor will operate on one phase after it is started, but it will require considerable more energy for the same load; that is, the efficiency of a polyphase motor operating single phase is very low.
- 40. Small single-phase squirrel-cage motors can be started without load by pulling the belt enough to bring the speed up nearly to synchronism and applying the load after full speed is attained; the torque while accelerating is only a small part of full-load torque. This method of starting is practically never used except with very small motors and rarely even

with them; special windings are usually provided for electrical starting. Electrically, self-starting single-phase motors may be classed as *split-phase motors*, *shaded-pole motors*, *single-phase series motors*, and *repulsion motors*. In each of these classes, torque is established electrically while the motor is at a stand-still.

SPLIT-PHASE MOTORS

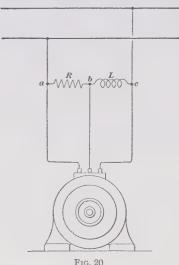
41. In the split-phase motor, a form of rotating field is established for starting by using two-phase or three-phase windings and supplying these windings with displaced electromotive forces obtained by the use of resistance and inductance or resistance and capacity. Fig. 19 shows a two-phase winding with a non-inductive resistor R in series with winding A and an inductor L in series with winding B; the two

windings are connected in parallel across the lines. The current in winding B is thus made to lag behind that in winding A, and if the resistance and inductance are correctly proportioned the currents can be made to differ enough in phase to produce an imperfect form of rotating field sufficient to start the motor. The windings are frequently so designed that the necessary phase displacement is caused by the windings



themselves, and outside resistance and inductance are rendered unnecessary. In some cases, one of the windings is a main, or working, winding, and the other is used only at starting, its circuit being opened manually by means of a switch after the motor has attained its speed.

Fig. 20 shows another method of starting a motor on singlephase mains. The two windings are provided with three terminals; the two outer terminals are connected to the mains, and the middle terminal to a point b between the resistor R



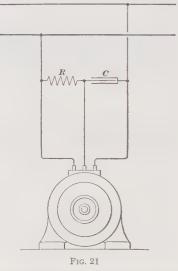
and the inductor L. The electromotive force between a and b differs in phase from that between b and c, so that the different windings of the motor are supplied with displaced electromotive forces suitable for starting. A switch is usually arranged to disconnect the resistor and the inductor automatically after the motor has come up to speed, thus placing the two primary windings in series across the single-phase circuit.

Fig. 21 shows a starting arrangement similar to Fig. 20,

except that a condenser C is used instead of the inductor L. With this combination, the resistor and the condenser are sometimes left in circuit after the motor has attained speed, because the condenser counteracts the self-induction of the motor and thus raises its power factor to such an extent that the small amount of loss in the resistor is more than made up.

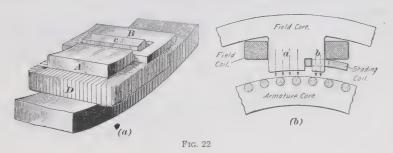
SHADED-POLE MOTORS

42. Fig. 22 shows an interesting starting arrangement used to a great extent for small single-phase fan motors. Each pole piece A, view (a), is



provided with a magnetizing coil D; in the pole piece is made a

slot c, in which is placed one side of a rectangular copper stamping or coil B called a *shading coil*. In some cases, the shading coil consists of a number of turns of wire with the two ends joined together so as to make a closed circuit. The primary coil D sets up a magnetic flux a, view (b), and the com-



bined effect of coils D and B sets up a flux b through the part of the pole face covered by coil B. The flux passing through the shading coil is out of phase with that through the main coil and induces currents that are out of phase with the main flux, thus producing the effect of a shifting magnetic field to a sufficient extent to bring a small squirrel-cage rotor up to speed.

SINGLE-PHASE SERIES MOTOR

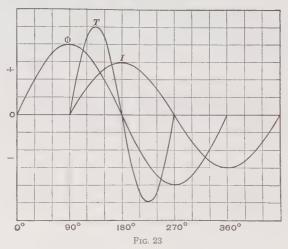
43. If a series-wound direct-current motor with laminated fields is supplied with alternating current, it will start and accelerate with good torque. Since the field and the armature are in series, the current in each reverses at the same instant, and in a direct-current motor, when the currents in both field and armature are reversed simultaneously the direction of rotation remains unchanged.

The design of such motors has been so improved that they operate with little sparking. They have practically the same characteristics as the corresponding direct-current machine; the speed increases with decrease in load, and the torque is large at starting and decreases with increase in speed. The frequency on which these motors are operated must be low (twenty-five cylces or under), and as a frequency of twenty-

five has become standard in railway work, single-phase series motors have been designed chiefly for that frequency. One advantage of the motor is that it will operate on either direct or alternating current. Because of its speed characteristics, it is not adapted for industrial service in which practically constant speed is required at all loads, nor is it adapted for service in which the load may become very small at any time.

REPULSION MOTORS

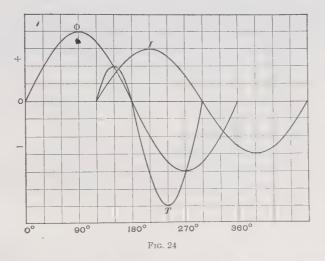
44. Theory.—If the poles, Fig. 3, are excited by single-phase alternating current, alternating magnetic flux is set up through the secondary circuit and current is induced in it 90 electrical degrees behind the flux. These phase relations are shown in Fig. 23, in which curve ϕ represents the flux set up by the primary current and curve I the induced secondary



current. The torque at any instant is the product of the instantaneous flux and the current; this torque is represented by the curve T, the ordinates of which are proportional to the products of the instantaneous ordinates of curves ϕ and I.

At 90 electrical degrees, ϕ is maximum positive and its rate of change is 0; I is therefore 0. Their product 0 gives one

point in the curve T. At 135 electrical degrees, the flux has decreased and the current has increased until their product gives the maximum positive point on the torque curve. At 180 electrical degrees, the flux is 0, the current maximum positive, and the torque 0. At 225 electrical degrees, the flux has become negative, the current is still positive, and the product of the two numerical values gives the maximum negative value of torque. The remainder of the curve T is derived in the same way. Between 90 and 180 electrical degrees, the torque is positive; between 180 and 270 degrees, negative;

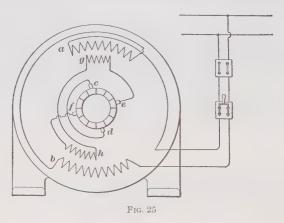


between 270 and 360 degrees, positive; and so on, reversing every quarter cycle.

45. In referring again to the secondary element $a\ d\ b\ c$, Fig. 3, it will be seen that friction and inertia prevent its sudden movement in response to the reversing torque. The most this torque can do is to cause slight oscillations of the secondary. If the element could move quickly enough, it would be *repelled* during the first quarter cycle to a position in which its plane would be parallel to the direction of the lines of force. If the rotating element in Fig. 3 could move to such a position, the reversing magnetic flux could then exert no further influence

on it, and such an arrangement could not therefore produce rotary motion.

46. The conditions shown in Fig. 23 could prevail only when the secondary current is in phase with the secondary induced electromotive force; that is, when the secondary circuit has no self-induction. Fig. 24 shows more common conditions; here, the secondary current lags behind the secondary electromotive force, or is more than 90 electrical degrees from the primary flux ϕ . The torque curve T is derived, as before, by making its ordinates proportional to the products of the ordinates of the flux and current curves. In this case the

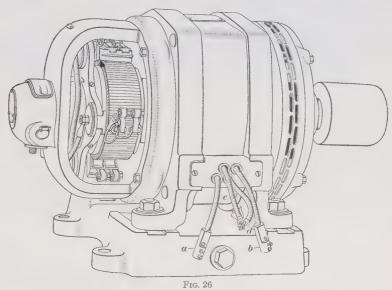


larger part of the torque is negative, as shown by the negative loop of the torque curve being larger than the positive loop. The positive loop may be considered an attractive force, and the negative loop a repelling force.

47. Commuted Winding.—By arranging the conducting elements of the secondary so that they are closed, or short-circuited, only when in position to take advantage of this repelling force, the secondary will rotate, forming a repulsion motor. This arrangement is effected by winding the secondary with coils and connecting them with the segments of a commutator, essentially the same as for a direct-current motor. Interconnected brushes in contact with the proper points on the

commutator short-circuit secondary coils when in position to be affected by the repelling force, leaving the coils in other positions open-circuited.

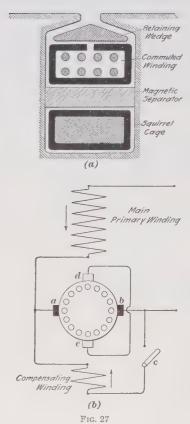
48. Fig. 25 indicates the windings of a single-phase repulsion motor, with primary windings a and b connected with a single-phase circuit through a switch and fuses. The short-circuiting brushes c and d are called *energy brushes* because through them is established the current that produces the torque. Two additional brushes e and f, displaced approxi-



mately 90 electrical space-degrees from the energy brushes, are connected with a winding gh on the primary. This winding acts as the secondary of a transformer, receiving its energy from the primary windings a and b. Current in the circuit of winding gh serves to maintain the power factor at nearly unity and to make the speed of the motor stable; this winding is therefore called *compensating*, and brushes e and f are the *compensating brushes*.

49. The speed of such motors can be regulated by changing the resistance of energy and compensating circuits. Increasing

the resistance in the energy circuit or decreasing the resistance in the compensating circuit reduces the speed, and vice versa. For speed regulation, the two circuits are closed through a controller having independent resistances for each circuit; a movement of the controller handle simultaneously changes



the resistance in both circuits, thereby decreasing or increasing the speed, according to which way the handle is moved. Standard controllers for this purpose give a range of speed from 40 per cent. below to 10 per cent. above normal, provided the motor is operating with full-load torque for all speeds; the output varies directly with the speed.

50. Fig. 26 shows a typical single-phase repulsion induction motor with four primary terminal leads a, b, c, and d brought out from two main primary windings. These leads are shown joined for connection with a 220-volt circuit, the connections being made with terminals a and b; by joining lead c to lead a and lead d to lead b the motor can be operated from a 110-volt circuit. Two of the sets of brushes shown on the

commutator are energy brushes and the other two compensating brushes. Such motors are made only in sizes up to about 10 horsepower; they compare favorably with polyphase induction motors of corresponding ratings in starting torque, maximum overload capacity, efficiency, and power factor.

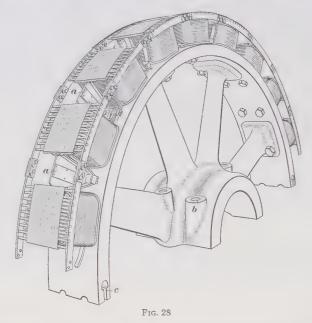
51. In one of the most successful single-phase repulsion induction motors the secondary has two windings, a commuted winding and a squirrel-cage winding, between which each slot contains a magnetic separator, as shown in Fig. 27 (a). The connections are shown in (b). In starting, the main primary winding is connected through the compensating brushes a and b, while the circuit of the compensating winding is open at the switch c. The magnetic separator gives the squirrel-cage conductors high inductance at the high frequency while starting, thus preventing current from building up in them until the rotor approaches synchronous speed, at which speed the secondary frequency is lower.

Most of the starting torque is therefore developed by the current in the commuted winding and in the circuit of the energy brushes d and e, as in a repulsion motor. As the speed increases, however, the secondary frequency decreases and the induced current in the squirrel-cage winding increases, until the motor operates nearly the same as a squirrel-cage motor. At a speed near synchronism the switch c closes automatically, after which the effects of the commuted winding and the compensating winding combine to keep the power factor nearly at unity.

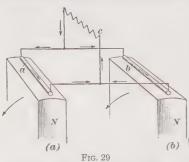
SYNCHRONOUS MOTORS

52. Synchronous motors are made to operate on either single-phase or polyphase systems, and are so called because they always run in synchronism with the alternator that drives them. In construction they are almost identical with alternators, and they always consist of the two essential parts, field and armature, either of which may rotate. The field, which is usually the rotating part, must be excited from a separate continuous-current machine in the same way as an alternator; collector rings are therefore needed to carry the exciting current to the rotating field, as on an alternator. In fact, either an alternator or a synchronous motor can be made to serve the purpose of the other, although when designed for motor service the rotating field is generally provided with a

squirrel-cage starting winding, as shown by the partial construction in Fig. 28. Uninsulated bars in slots in the pole



faces are fastened to short-circuiting rings at the ends. The vanes a between the poles are to prevent air-currents from passing between the poles instead of through ducts in the arma-



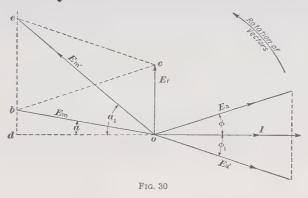
ture. The holes b and the slots c are for bolting and keying the two halves of the hub and the rim.

53. Theory.—Fig. 29 indicates similar elements of two alternators, N representing north poles, one on each machine, and a and b conductors occupying similar posi-

tions on the two machines. The poles N are assumed to be rotating in the direction indicated by the curved arrows. At

the instant indicated, the voltages generated in the two conductors a and b are exactly opposed to each other in the circuit connecting them, or 180 time-degrees apart, as indicated by the small arrows. These two voltages unite, however, to cause current in an external circuit c. If the speeds and field strengths of the two machines are properly adjusted, no interchange of current will occur between them, but the currents from the two will unite to form the current in the external circuit. This is the ideal condition for parallel operation of two alternators.

If either alternator, say (b), is disconnected from the source of mechanical power driving it, this machine will cease to furnish current to the external circuit, but will continue to run



as a motor, taking current from the other machine a in proportion to the motor losses and the motor load. Machine (a) continues to operate as an alternator and delivers current to operate machine (b). The motor (b) does not remain in exact phase opposition to the alternator; the voltage in conductor b is now behind that in conductor a 180°+ an angle proportional to the motor load. If the load is increased, this angle increases until the load becomes so great that the motor pulls out of step and stops.

54. The machine operating as a motor therefore generates voltage nearly opposed, or counter, to that of the generator; the resultant of these two voltages causes the current through the two machines. Fig. 30 shows the conditions. Vector E_a

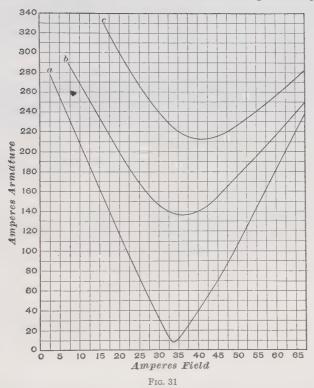
represents the alternator voltage; E_m , the motor voltage, a little more than 180 time-degrees behind E_a ; and E_r , their resultant, which causes the current represented by vector I. This current is assumed to be lagging behind the alternator voltage by an angle ϕ . The resultant E_r is found in the usual way by drawing from the extremity of E_m a line b c equal and parallel to E_a and connecting the origin o with the extremity c of this line.

55. Change of Field Excitation.—If the field current of a synchronous motor operating with lagging line current is gradually increased while the load remains constant, the line current at first decreases to a minimum value and then increases again. The motor speed cannot change, for it must remain in synchronism with the alternator; nor does the line voltage change. The motor voltage, however, must change with change of field excitation.

Assume, for example, that with the conditions shown in Fig. 30, the motor field excitation is increased indefinitely; the line current I will first become minimum and then increase again to its original value. The resultant voltage E_r causing this current must then be the same as before. The line voltage has not changed, nor has the power taken from the line, but the phase relation of the line current and the line voltage has changed from an angle of lead ϕ to an angle of lag ϕ_1 such that $IE_a\cos\phi=IE_a'\cos\phi_1$. As E_a and E_a' are the same in value, simply having changed in phase relation with the line current, $\cos\phi=\cos\phi_1$, or $\phi=\phi_1$.

Increasing the motor field excitation must have increased the motor voltage from E_m to some value $E_{m'}$. As the motor load is constant, $I E_m \cos a = I E_{m'} \cos a_1$, or $E_m \cos a = E_{m'} \cos a_1 = o d$, in which $E_m \cos a$ and $E_{m'} \cos a_1$ are the components of the motor voltages in direct opposition to the line current. The extremities of vectors E_m and $E_{m'}$ must then be on a line d e perpendicular to the direction of the current vector. As E_r is the vectorial sum of E_a' and $E_{m'}$, the latter vector is fixed by drawing a line c e parallel to E_a' and equal to it in length, fixing the point e on the vertical d e.

Fig. 30 shows that increasing the field excitation of a synchronous motor changes the phase relation of the line voltage from lead to lag, or, as this change is usually expressed, a lagging line current is changed to a leading line current. Between the two conditions assumed for this illustration is a field excitation at which the line current and the line voltage are in phase;



that is, the power factor is unity. At this point the line current is minimum, a desirable condition in alternating-current circuits.

56. Characteristic Curves.—Fig. 31 shows the change of line current caused by changing the excitation of a three-phase synchronous motor with three constant-load conditions; this motor is wound for sixty cycles, 2,300 volts, 840 kilovolt-amperes, and 720 revolutions per minute. Curve a shows the

effect with no load; as the field amperes are increased, the line current decreases to the minimum of 8 amperes per phase at a field current of about 34 amperes. This minimum line current indicates that the line voltage and the line current are in phase; the angle of the phase difference between voltage and current is therefore 0, and the power factor is unity. The entire power input to the motor is then required for the motor losses and it can be found by the formula for three-phase power; thus, $\sqrt{3} I E \cos \phi = \sqrt{3} \times 8 \times 2,300 \times 1$

$$\frac{\sqrt{3} \ I \ E \cos \phi}{1,000} = \frac{\sqrt{3} \times 8 \times 2,300 \times 1}{1,000} = 32 \text{ kilowatts.}$$

With the load represented by curve b, the minimum line current is 136 amperes, occurring when the field current is 36 amperes. The input is then $\frac{\sqrt{3}\times136\times2,300\times1}{1,000}$ =542 kilo-

watts. The losses are now considerably greater than at no load; if they are assumed to be 42 kilowatts, the output in mechanical power is 500 kilowatts. Curve c represents another load condition with a minimum line current of 212 amperes, occurring when the field current is 41 amperes. The power input to the $\sqrt{3} \times 212 \times 2.300 \times 1$

motor is then $\frac{\sqrt{3}\times212\times2,300\times1}{1,000}$ = 845 kilowatts, and if the

loss is assumed to be 45 kilowatts the output is 800 kilowatts. At each of these three loads the input is the same at all line currents; the change in line current corresponds to the change of power factor $\cos \phi$ caused by the change of field excitation.

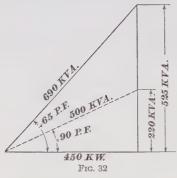
57. With any load condition, the power factor can be adjusted to any value between wide limits, as shown in Fig. 31, by adjusting the field current. Increasing or decreasing the field excitation for the point at which minimum armature current is obtained decreases the power factor; increased excitation gives leading line current, and decreased excitation gives lagging current. The power at any power factor can be measured by wattmeters, but to avoid errors when making tests, the field current is customarily adjusted for minimum armature current and the wattmeter readings are then checked by comparing them with the power computed from the voltmeter and ammeter readings.

58. Synchronous Condensers.—The effect of a condenser in an alternating-current circuit is to cause leading current, as explained in Alternating Currents, Part 1. Since a synchronous motor with overexcited fields has the same effect, the name synchronous condenser or rotary condenser is often applied to a motor operated for this purpose. Distribution systems loaded with induction motors and transformers have low power factors that cause lagging current, which can be corrected by the use of synchronous condensers. When the limit of generating and distributing ability in such a system has been reached, the installation of one or more synchronous condensers will raise the power factor and thus make possible the delivery of more energy with the same current by reducing the idle, or wattless, current.

This effect may be produced by overexciting the fields of a synchronous motor used to drive a pump, a compressor, or some other steady load, thus making the motor output partly electrical and partly mechanical; or, an idle alternator may be allowed to run as a motor with overexcited field. If a water-wheel-driven alternator is so used, the water can be entirely shut off; but if the alternator is steam-turbine-driven, about the same amount of steam should be admitted to the turbine as would be required to run the set at full speed without load. Without this steam, the turbine buckets might overheat, owing to excessive windage. A machine designed purposely for a synchronous condenser usually has a very small air gap, or clearance, between the stator and the rotor in order that maximum overexcitation may be obtained.

59. Selection of a Synchronous Condenser.—If a machine is selected to operate as a synchronous condenser only, its capacity should be determined according to the power used in the circuit and the power factor. For example, the capacity of a synchronous condenser to run without motor load and raise the power factor from 65 per cent. to 90 per cent. in a circuit carrying a total load of 450 kilowatts can be calculated as illustrated in Fig. 32. The results of the calculations are in most cases here given approximately correct.

The power component, 450 kilowatts, divided by the power factor .65 gives the kilovolt-amperes 690; the wattless component is $\sqrt{690^2-450^2}=525$ kilovolt-amperes. With the power factor 90 per cent., the apparent load is $450 \div .9 = 500$ kilovolt-amperes, and the wattless component $\sqrt{500^2-450^2}=220$ kilo-



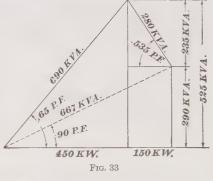
volt-amperes. The condenser must supply the difference between these two wattless components, or 525-220=305 kilovolt-amperes, at 0 power factor.

60. If the synchronous machine is to operate as both a motor and a synchronous condenser, its capacity must be equal to both requirements. Assuming the same load and power fac-

tor conditions as in Fig. 32, but with an additional motor load of 150 kilowatts, the problem can be solved as illustrated in Fig. 33, the results of calculations being given in round numbers, as before.

The total power component is now 450+150=600 kilowatts.

With the power component $450 \,\mathrm{kilowatts}$ and powerfactor $65 \,\mathrm{per}$ cent, the corresponding apparent load is $690 \,\mathrm{kilovolt}$ -amperes and the wattless component $525 \,\mathrm{kilovolt}$ -amperes, as before. With the power component $600 \,\mathrm{kilowatts}$ and the power factor $90 \,\mathrm{per}$ cent., the apparent load is $600 \div .9 = 667 \,\mathrm{kilovolt}$ -amperes and the



wattless component $\sqrt{667^2-600^2}=290$ kilovolt-amperes. The condenser must then supply a wattless component of 525-290 = 235 kilovolt-amperes in addition to its power component of 150 kilowatts. Its rating must therefore be $\sqrt{150^2+235^2}$

=280 kilovolt-amperes and its power factor $150 \div 280 = .535$, or 53.5 per cent.

- 61. Starting Synchronous Motors and Condensers. The very high starting current required by the earlier types of synchronous motors was objectionable on account of disturbance of the line voltage. Small induction motors were generally used for starting, but they were disconnected from the synchronous motors after the latter were up to speed and connected with the line. The later types of synchronous motors have squirrel-cage windings over the pole faces (Art. 52) and start readily as induction motors, with considerable torque on reduced voltage from autotransformers. The speed can thus be brought to a point from which the motor will pull into synchronism when switched on to the circuit.
- 62. In order that the rush of current shall not be excessive when the line switch is closed, the slip as an induction motor must not be large; but, on the other hand, the resistance of the squirrel-cage winding must be enough to give good starting torque. The ideal condition would be with a squirrel-cage winding of high resistance at start and with decreasing resistance as the speed increases. This condition can be approached by taking advantage of the resistance caused by skin effect, or eddy currents, in the conductors of the starting winding.

At start, the frequency of the current induced in the starting winding is the same as that of the primary current; as the speed increases, the frequency of the secondary current decreases until at synchronism it is zero. *As the skin effect varies with the frequency, it is greatest at start and decreases as the speed increases. By proportioning the bars of the squirrel-cage winding so that the skin effect will be large, the effective resistance can thus be made to vary so as to obtain high starting torque and comparatively low slip.

63. Insulation of Field Windings.—The field windings of synchronous motors must be specially well insulated, because very high electromotive forces may be induced in them while

starting. During the starting period, both the squirrel-cage winding and the field coils act as secondaries, the flux through them reversing at a frequency that corresponds to the primary frequency at first and decreasing as the speed increases.

64. Applications.—Synchronous motors are best adapted to loads that are fairly continuous and steady. Frequent starting should be avoided, and fluctuating loads are not generally desirable. Ideal applications are pumps, compressors, blowers, and fans that operate for long periods without stopping and with little change of load. Provision must usually be made to start such motors with only a fraction, usually less than one-third, of full-load torque.

SYNCHRONOUS CONVERTERS

CONSTRUCTION

- 65. A synchronous converter is a machine for changing alternating current to direct current or direct current to alternating current; rotary transformer and rotary converter are older names for the same machine. Synchronous converters are largely used in connection with electric-railway work to convert the alternating current with which electric energy is economically transmitted to direct current for operating the car motors. A similar conversion is necessary at many electrolytic and electroplating plants.
- 66. In its essential features and general appearance, a synchronous converter is much like a direct-current generator; it has also some features of construction and some operating characteristics in common with a synchronous motor having a rotating armature. Fig. 34 shows the general appearance of a typical three-phase rotary converter. The armature has only one winding in the form of a closed drum; at one end the armature conductors are connected with segments of a commutator, and at the other end are collector rings connected with some of the commutator segments.

When the armature rotates in the magnetic field, alternating electromotive forces are induced in the armature conductors. Through the commutator, these electromotive forces may be used to establish direct current in an external circuit, and through the collector rings the same forces may be used to establish alternating current in another circuit. In fact, alternating current can be taken from one end and direct cur-

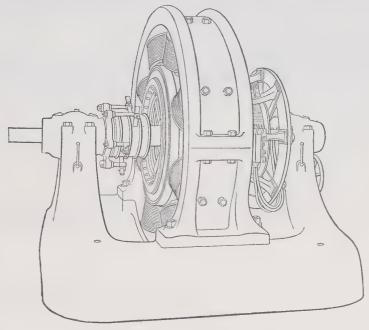


Fig. 34

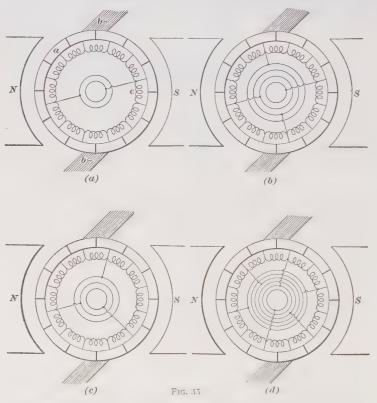
rent from the other at the same time. Suitable current supplied to either the commutator or the rings will cause the machine to run as a motor and in so doing act as a generator delivering current from the other end.

67. As generally used, synchronous converters are supplied with alternating-current energy and operate as synchronous motors, while direct-current energy is delivered from the commutator end. When the machine is run as a direct-current

motor to deliver alternating current, it is generally called an inverted synchronous converter; when run by mechanical power and made to deliver both kinds of current, it is called a double-current generator.

INTERNAL CONNECTIONS AND VOLTAGE RATIOS

68. Fig. 35 shows connections of armatures for bipolar synchronous converters. The segments a represent the bars of the commutator, on which rest the brushes b+ and b-.



The armature coils c are represented for convenience inside the commutator, though it must be remembered that these coils are in slots on a drum; also, that the ends of the coils

are connected with the commutator bars, as shown, and that extra leads extend from some of the bars through the slots and to collector rings on the shaft at the end of the armature opposite the commutator. These rings also are represented inside the commutator. To make the connections more simple, only twelve commutator bars are represented, though in practice many more bars and armature coils are used. With the brushes in the positions shown relative to the poles, the following relations between the alternating-current and the direct-current voltages exist:

69. Fig. 35 (a) shows the connections for a single-phase converter; diametrically opposite bars are connected with the collector rings. The electromotive force between these rings is maximum when the bars with which they are connected are directly under the brushes and minimum, or zero, when these bars are midway between the brushes. The electromotive force between the rings is therefore alternating, with its maximum value equal to the direct-current voltage. As the effective value of a sine-wave alternating electromotive force is .707 times its maximum value, the effective voltage E_{a1} between the collector rings is .707 times the direct voltage E_{d} across the brushes; or, in single-phase converters,

$$E_{a1} = .707 E_d$$

70. Fig. 35 (b) shows two-phase, or quarter-phase, connections with four rings connected with four bars spaced equally around the commutator. Each pair of rings belonging to a phase is connected with bars diametrically opposite each other, as in single-phase connections, and the voltage between either pair of rings in a two-phase converter is

$$E_{a2} = .707 E_d$$

71. In three-phase connections, Fig. 35 (c), three bars spaced equidistant from one another are connected with three rings. The maximum voltage between any two collector rings can be proved geometrically to be .866 times the direct-current voltage, and since the effective voltage is .707 times the maximum voltage,

$$E_{a3} = .707 \times .866 \ E_d = .612 E_d$$

72. Six-phase connections are made by joining six collector rings with six bars at equidistant points on the commutator, as in Fig. 35 (d). The external connections are made by providing each secondary coil of the three-phase transformer supplying current with two leads and connecting each pair of leads with a pair of rings. The rings of each pair so formed must be connected with commutator bars either diametrically opposite each other, or 120 electrical degrees apart; the former connections are known as six-phase diametrical and the latter as six-phase double delta. With six-phase diametrical connection, the voltage per phase bears the same relation to the direct voltage as in a single-phase converter; and with six-phase double-delta connection, the relation is the same as in a three-phase converter, or

 E_{a6} (diametrical) = .707 E_d E_{a6} (double delta) = .612 E_d

73. Multipolar Connections.—The connections between the collector rings and the commutator hars in multipolar synchronous converters may be the same as shown in Fig. 35, provided the armature is series-wound, or wave-wound. If parallel-wound, or lap-wound, each collector ring must be connected with one bar for each pair of poles, and the bars with which each ring is connected must be 360 electrical space-degrees apart. For example, in a four-pole rotary with a parallel-wound armature, each ring must be connected with two bars 360 electrical space-degrees, or 180 mechanical space-degrees apart. The electrical space-degrees between bars with which the rings of each phase are connected are in all cases the same as shown in Fig. 35, namely, 180 for diametrical connections and 120 for three-phase and six-phase double-delta connections.

OPERATING CHARACTERISTICS

74. Alternating-Current Operation.—When operating in the usual way, with alternating current, a synchronous converter has practically the same operating characteristics as a synchronous motor; it runs in synchronism with the supply current and changing the field excitation does not affect the

speed. Such a change does, however, affect the power factor, and to some extent the ratio of the alternating voltage to the direct voltage. Synchronous converters, if specially designed for the purpose, can therefore be used to improve the power factor.

75. Direct-Current Operation.—When operating as an inverted synchronous converter, the characteristics resemble those of a shunt-wound direct-current motor. Weakening the field increases the speed, and this result sometimes follows the demagnetizing effect of lagging current in the alternating-current circuit. If the latter circuit is short-circuited, the heavy alternating current may so weaken the field as to cause excessive speed.

Moreover, when a compound-wound converter is operating in the usual way in parallel with other converters or with storage batteries, the opening of the alternating-current circuit-breaker causes the converter to operate as a direct-current motor with the direction of current reversed in the armature and series field; as the series field then opposes the shunt field, a weakened field and high speed results. Machines intended for operation as inverted synchronous converters should therefore be shunt-wound.

All synchronous converters are liable through accident to attain dangerous speeds by power supplied through the direct-current end. To guard against this, every synchronous converter is equipped with a device that automatically opens the direct-current circuit when the speed exceeds a given limit. There is also a slight chance that the alternating-current source of energy may, by accident, attain a high speed. For instance, waterwheel-driven alternators may run at nearly double speed due to failure of the waterwheel governor. In such cases, all synchronous apparatus on the line operates at correspondingly increased speed. Synchronous converters are designed to stand double normal speed, and safety devices on the alternating-current side are therefore unnecessary. A device is also commonly provided to oscillate the armature endwise enough to produce even wear of the commutator by the brushes.

76. Starting.—Synchronous converters can be started: (1) by means of induction motors direct-connected to the converter shafts; (2) as direct-current motors where such current is available, or (3) as alternating-current motors. The last method is most common. A modified type of squirrel-cage winding is embedded in the pole faces, giving induction-motor characteristics in starting. A field break-up switch opens the field circuit in several places to prevent the induction of excessively high voltages in the field windings by the alternating flux in the poles while starting. Methods of starting and synchronizing converters are fully discussed in another Section.

TABLE I

COMPARISON OF A GENERATOR AND A SYNCHRONOUS CONVERTER AT 100 PER CENT. POWER FACTOR

Function of Machine	Heating Effect of Given Current Per Cent.	Current Capacity for Given Heat- ing Effect Per Cent.
Direct-current generator	100	100
Single-phase converter	147	82
Two-phase converter	39	161
Three-phase converter	59	131
Six-phase converter	27	194

77. Heating Effect.—With any given current output, the heating effect in the armature of a polyphase synchronous converter is less than it would be if the same machine were mechanically driven as a generator with the same current output. The current in the armature bars is approximately equal to the difference between the direct and the alternating current, and, therefore, its heating effect is less than that of direct current for the corresponding output.

The heating of conductors nearest the tapping points is the greatest. Increasing the number of tapping points produces a more uniform heating of the armature conductors and allows a greater output. This is the reason for the increase in capacity

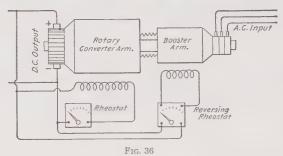
with an increase in the number of phases. The relative heating effects and the relative carrying capacities for a given heating effect are as recorded in Table I. These comparative figures are for a given machine used as a generator or as a converter and are true only when the alternating current and electromotive force are in phase; if out of phase, the heating effect in the synchronous converter is increased and the relative current capacity correspondingly decreased.

- 78. In a single-phase converter, the coils near the tapping points carry more current than they would if the machine were mechanically driven as a direct-current generator, making the heating effect greater and the carrying capacity for a given heating effect less. In a polyphase converter, the current is less in all coils than it would be if the same machine were used as a generator with the same direct-current output, resulting in decreased relative heating effect. Polyphase converters are therefore made smaller than direct-current generators for the same outputs. For example, a six-phase synchronous converter need be only about one-half as large as a direct-current generator for the same output with the same heating.
- 79. Commutation.—The commutation in a synchronous converter is better than that in a non-commutating-pole generator with the same direct-current output, because the effects of direct current and alternating current neutralize each other to some extent in the converter armature. Considerably larger currents can therefore be commutated successfully by a converter than by the corresponding direct-current generator. However, because of decreased heating effect in synchronous converters, commutation rather than heating formerly limited their output. Especially was this true in railway work, in which the load is subject to wide variation. The machines were therefore larger than necessary for cool running, because of liability to sparking and flashing at the commutator with the excessive currents occasionally required.
- 80. Commutating-Pole Synchronous Converters. Commutating poles have so increased the commutation limit of all direct-current dynamos that synchronous converters

with such poles are made much smaller for a given output than was possible with non-commutating-pole converters. The newer machines are very serviceable in all synchronous-converter work, and especially so in high-voltage direct-current systems. In some cases, excessive momentary overloads up to more than three times the normal rated capacity of the machine are made possible by the commutating poles. In starting such machines with alternating current, however, excessive sparking occurs at the commutator if the brushes remain in contact during the starting period. Converters for starting by this method are therefore provided with devices for lifting the brushes from the commutator while starting.

REGULATION OF DIRECT-CURRENT VOLTAGE

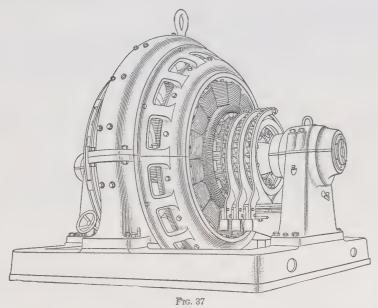
81. When a synchronous converter operates on alternating current, the direct-current voltage can be regulated by means of any of the following devices and methods: (1) By an



alternating-current synchronous booster; (2) by a regulatingpole synchronous converter; (3) by an induction regulator or a regulating transformer; (4) by a direct-current booster; and (5) by adjustment of field excitation.

82. Synchronous Booster Converter.—A synchronous booster is an alternating-current generator with its rotating member, which may be either armature or field, mounted on the same shaft as the armature of the synchronous converter. The field of the generator has the same number of

poles as the synchronous converter and is excited by current from the direct-current end of the converter, as shown in Fig. 36; the excitation can be adjusted manually or automatically in either direction. Alternating current enters the booster, and the voltage is raised or depressed, as required, in the booster armature, thus regulating the direct-current voltage. The booster and the converter are compactly assembled as a unit, as shown in Fig. 37; current from the booster armature passes directly into the converter armature.

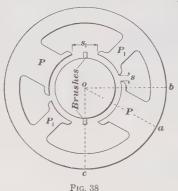


Any necessary range of voitage can be provided for in the design of the booster and the converter, though 15 per cent. each way from normal voltage is usually sufficient. Automatic adjustment can be provided, so that the converter will carry its proper share of the load when operating in parallel with other converters or with storage batteries.

83. Regulating-Pole Converter.—The fixed relations between alternating and direct voltages in a rotary converter, as given in Arts. 69 to 72, inclusive, exist only when the direct-

current brushes are so placed that the direct voltage equals the maximum alternating voltage when the collector rings are connected diametrically, as in Fig. 35 (a) and (b) and .866 times this value with the three-phase connection, Fig. 35 (c). By changing the direction of the magnetic flux, the relation between the two voltages can be varied.

In the regulating-pole, or split-pole, converter, each pole consists of two parts, as shown in Fig. 38, a main part P and a regulating part P_1 separated by a narrow polar space s. Between these combination poles are wider polar spaces s_1 , opposite which the brushes are placed. The illustration represents a two-pole machine, but the principle applies to multi-



polar machines also. When only the main poles are excited, the general direction of the lines of force is through the center lines of the main poles, as indicated by the line o a. If the excitation of the main poles is maintained constant and that of each regulating pole is increased in the same general direction as its main pole, the direction of the resulting flux swings toward the regulating pole, as indicated by

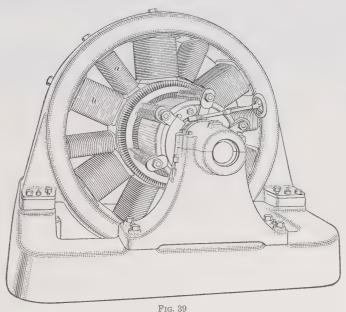
the line o b; exciting the regulating pole in the opposite direction causes the resulting flux to swing toward the line o c. The direction of the resultant flux can thus be varied through a wide angle.

This change in the direction of flux affects the ratio of voltage transformation, permitting a considerable range of direct-current voltage regulation with practically constant alternating voltage. Fig. 39 shows a 500-kilowatt, 240-300-volt regulating-pole rotary converter, in which a is a regulating pole and b a main.

84. Induction Regulator and Regulating Transformer.—Induction regulators and regulating transformers

are described in another Section. By means of either device. the voltage at the collector rings can be adjusted either manually or automatically, thus making corresponding adjustments of voltage at the commutator.

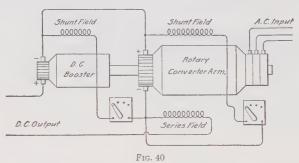
85. An induction regulator is a transformer with a primary core capable of being rotated inside the secondary core so that the primary flux threading the secondary coils can be adjusted at will. The primary winding is connected



in shunt across the circuit to be regulated, and the secondary winding is connected in series with the circuit. By adjusting the angular position of the primary core the secondary voltage can be boosted or lowered.

86. A regulating transformer is an ordinary static transformer provided with numerous taps on the secondary winding and a switching device by means of which the part of this winding in series with the circuit to be regulated can be adjusted: the primary winding is shunted across the circuit.

87. Direct-Current Booster.—A booster generator can be connected in series with the direct-current circuit, as in Fig. 40, and its voltage made to increase or decrease the voltage from the rotary converter. The booster can be shuntwound and excited from the rotary, as shown, or series-wound. The booster is usually mounted on the same bedplate as the converter, and its armature shaft is continuous with the converter shaft or coupled to it. This combination is heavier, more expensive, and requires more space than the synchronous booster converter described in Art. 82, and, moreover, it is more troublesome, since two commutators must be maintained.



88. Adjustment of Field Excitation.—The direct-current voltage of a rotary converter can be regulated within a very limited range by adjusting the field excitation. Changing the field excitation changes the phase relation of the alternating current and voltage, as explained in connection with synchronous motors. The higher values of direct-current voltage may be established by producing a leading alternating current. To increase the effect of change of field excitation, inductors are sometimes included in the alternating-current circuit or inductance is incorporated in the transformers. Voltage regulation by field adjustment is therefore at the expense of power factor. Adjustments can be made by means of a rheostat in the converter field, or a compound field winding can be used. Both are commonly employed, and the series field and inductors can be adjusted to keep the voltage constant from no load to full

load, flat compounding, or to increase the voltage with increasing load, overcompounding. Compound-wound converters do not operate satisfactorily in parallel with storage batteries; only shunt windings are advisable in such service.

DOUBLE-CURRENT GENERATORS

89. When a synchronous converter is used as a double-current generator, its output can be delivered as direct current, as alternating current, or partly as one and partly as the other, provided, of course, the combined output on the two sides does not exceed the capacity of the machine.

Double-current generators are sometimes useful where direct current is desired for utilization near at hand, and alternating current for transmission to distant points.

90. The heating effect and armature reaction in a double-current generator are much greater than in a synchronous converter delivering the same total output. In the converter armature conductors, the current is approximately the difference between the motor current and the generator current, and in the double-current generator, approximately the sum of the currents from both ends is effective, both in heating and in causing armature reaction. Compound field windings are common, but the shunt field is usually excited from a separate source, because, if self-excited, the demagnetizing action of lagging alternating current affects the voltage considerably.



INDUSTRIAL MOTOR APPLICATIONS

GENERAL CONSIDERATIONS

CHOICE OF SYSTEM

1. The successful operation of a motor depends on its intelligent selection and application. However good its design and construction, a motor will not give its best service in an application for which it is not suitable. Its general class, its type, its characteristics, its degree of enclosure and mechanical structure, each must be considered in making a selection.

Almost any industrial plant can be equipped with satisfactory motors operating on either of the two available systems, namely, alternating current or direct current. The choice between the two is influenced by the available supply of electricity, by the distance that electricity must be transmitted, and by the nature of the work to be done. Some general considerations are here given to guide in making a choice.

2. Available Supply.—In equipping with motors an industrial plant located in a territory served by a reliable central station, the use of central-station power is usually more satisfactory and economical than installing a private generating plant, though this is not always the case. In any event, the system chosen should agree with that of the central station, so that emergency service can be obtained. Most central stations are prepared to supply either alternating current or direct cur-

COPYRIGHTED BY INTERNATIONAL TEXTBOOK COMPANY. ALL RIGHTS RESERVED

rent, but the latter is usually confined to comparatively small or thickly settled areas or to applications where it is peculiarly essential.

- 3. Distance of Transmission.—The energy loss in transmission circuits depends on the square of the current; therefore, long distance transmission at high pressure and low alternating current is more economical than at the low pressures common with direct current. The distance that direct-current energy can be transmitted economically depends on the voltage and on the quantity of energy. Energy at 500 to 600 volts is commonly transmitted 5 or 6 miles for electric railway work; 220-volt energy for industrial motors is limited to much smaller distances, possibly 1 mile, and 110-volt energy to approximately ½ mile. These limits are very approximate and are suggested only as guides; they must be varied according to the quantity of energy.
- 4. Nature of Work.—The work to be done may in some cases determine the choice of a system, because some work necessitates the characteristics of alternating-current motors and other work those of direct-current motors. These statements will be more fully explained later.

CHOICE OF MOTORS

5. Efficiency.—Efficiency is an important consideration in selecting motors, because the cost of energy varies inversely with the motor efficiency.

Let w =output, in watts, of a motor at efficiency e;

t = time, in hours, that motor operates;

 $c = \cos t$ of energy per kilowatt-hour;

C = total cost of energy.

Then.

$$C = \frac{w \ t \ c}{1,000 \ e}$$

If a motor operates 10 hours per day and 312 days per year, the annual cost per horsepower output at 1 cent per kilowatt- $C = \frac{746 \times 10 \times 312 \times .01}{1,000 e} = \frac{\$23.275}{e}$ hour is

Under these conditions the costs at different efficiencies ordinarily found in practice are as given in Table I. The annual cost per horsepower is proportional to the rate; thus, at 5 cents per kilowatt-hour, the values given in the table must be multiplied by 5.

TABLE I

COST OF ENERGY PER HORSEPOWER-YEAR
(312 days, 10 hours each, 1 cent per kilowatt-hour)

Efficiency	Annual Cost	Efficiency	Annual Cost	Efficiency	Annual Cost
-93	\$25.03	.87	\$26.75	.81	\$28.73
.92	25.30	.86	27.06	.80	29.09
.91	25.58	.85	27.38	.79	29.46
.90	25.86	.84	27.71	.78	29.84
.89	26.15	.83	28.04	.77	30.22
.88	26.45	.82	28.38	.76	30.63

For example, suppose a motor is to be selected for an output of 10 horsepower, 10 hours per day, where the cost of energy is 5 cents per kilowatt-hour, and two motors having at this output efficiencies of 84 and 87 per cent., respectively, are available. The annual saving by using the motor with the higher efficiency is found by multiplying the difference between the figures in the table corresponding to these efficiencies by the horsepower and the rate.

At 84 per cent	\$27.71
At 87 per cent	26.75
Difference	\$.96

Thus, $.96 \times 10 \times 5 = 48 per year saved.

6. Capacity.—At or near full rated load, a motor operates at its highest efficiency, and selection should be made accordingly. The motor should be capable of developing all the power required of it, but should not have a large surplus capacity. In general, the load should be from three-quarters to full rated motor capacity in order to obtain economical operation. A

motor operating at much less than three-quarter load generally has greater losses (lower efficiency) than a smaller motor operating at nearly full load, and the additional energy thus lost may soon equal in value the cost of a motor of suitable size.

When the load is of a varying nature, the motor must be large enough to carry the maximum load, although this maximum, if of not more than 1 or 2 hours' duration, can be carried as an overload on most motors rated for continuous duty. If the load is of very intermittent or periodic nature, a motor with appropriate rating can usually be obtained.

- 7. In selecting alternating-current motors, accuracy in determining capacities is especially important, because, at reduced capacities, such motors have both low efficiencies and low power factors. The power factor of a system on which a number of induction motors are operating at reduced loads may thus be made very low. The generators and the transmission circuits may be carrying full-load current, and a considerable portion of it may serve no useful purpose.
- 8. Speed.—As a general rule, a high-speed motor is less expensive than a motor for the same output at slow speed; therefore, a saving can be effected by selecting motors for the required outputs at speeds as high as can be used satisfactorily. Usually, the machine to be driven must operate at a specified speed, and the motor must be belted, geared, or otherwise connected to it in a way to obtain that speed. The motor speed must be such that this connection is practicable, and must not be too high for the safety of the motor itself.
- 9. Direct-Current Motors.—Direct-current motors are superior to alternating-current motors for some applications. For example, shunt-wound motors are preferable for applications requiring many speed adjustments with fairly constant speed at each adjustment; series-wound motors are superior for frequent starting with very high torque; and compound-wound motors for some applications requiring fairly high starting torque or occasionally heavy torque while operating.

TABLE II INDUCTION-MOTOR APPLICATIONS

Slip. Ring	Constant Speed	Compressors Starting against full pressure Flour-mill machinery Caroup drive Large groups Paper-mill machinery Batters Pumps Large plunger Pumps starting against full Hoists and winches pressure Woodworking machinery Large planers and matchers Large planers and matchers Capanage machinery Newspaper machines Super-anill machinery Newspaper machinery Charging machinery Charging machinery Skip hoists Starting against full Hoists and winches Charging machinery Charging machinery Skip hoists Starting against full pressure Noodworking machinery Charging machinery Skip hoists
Cage	High Slip	Cranes Cross-heads on machine tools Elevators Flywheel service Punches Shears Large band saws Motor-generator Equalizer sets Laundry extractors Slarting motors Motor-generator sets Rotary converters Sugar centrifugals Valves and gates
Squirrel Cage	Low Slip	Blowers Centrifugal Disk Positive Cement Machinery Crushers Grinders (various types) Concrete mixers Cotton-mill machinery Individual drive Line-shaft drives Except for very large and heavy groups Motor-generator sets Paper-mill machinery Pulp grinders Pumps Jordans Stuff chests Pumps Fumps Jordans Pumps Jordans Stuff chests Pumps Jordans Pumps

- 10. Alternating-Current Motors.—In comparison with direct-current motors, alternating current motors are generally more simple in construction, more durable, and require less attention while operating. With a few exceptions they are equally well suited to the work and in many cases are better. When alternating-current motors are selected, the merits of single-phase and polyphase motors and of the subdivisions of each of these two general classes must be considered.
- 11. Single-phase motors are generally applicable for industrial purposes only in small sizes up to 10, or possibly 15, horsepower. Starting rheostats are generally necessary with such motors of 5 horsepower and larger in order to keep the starting current low enough not to disturb the line voltage. Single-phase motors are available with different characteristics, some suitable for strictly constant-speed service and others for service where some speed variation is essential.
- 12. Polyphase motors include induction motors of the squirrel-cage type suitable for light-starting and constant-speed service, and the slip-ring type suitable for heavier-starting and for varying-speed service; they also include synchronous motors appropriate for light-starting and constant-speed service and for power-factor correction.

Squirrel-cage motors with low rotor resistance, resulting in low slip and correspondingly high efficiency are suitable for constant-speed applications where starting is fairly easy. For applications requiring more starting torque squirrel-cage motors with high rotor resistance, high slip, and correspondingly low efficiency are more appropriate. Table II gives a general idea of the selection of polyphase motors for many services.

GROUP DRIVE AND INDIVIDUAL DRIVE

13. Arranging several machines to receive power from a shaft driven by a single motor is called **group drive**. Operating each machine by a separate motor is called **individual drive**. Group drive is the original method, since the substitution of a motor for an engine to drive a line shaft was easily made; the

group then included all the machines formerly driven by a single engine. But long line shafts must be carried in many bearings with some friction loss in every bearing, especially if the shaft is not kept in perfect alinement, which is a difficult thing to do. Moreover, the shaft must run continuously, even though the various machines are used infrequently.

14. Subdivision of the machines into small groups, each belted from a comparatively short shaft driven by a smaller motor is more economical than the single large motor plan. because each motor need operate only when one of its machines is in use. For many purposes, however, the most rapid production and the greatest economy in time and in the use of energy are obtained when each machine is driven by its individual motor. In any case, whether for group drive or individual drive, the motor selected should be neither too small nor too large: its application should be such that it will not operate for long periods at a small fraction of its rated capacity. If several machines can be grouped and driven by one motor so as to utilize from three-fourths to full motor rating while the motor is running, group drive may be found economical; but if only one or two machines operate simultaneously taking less than half the power of which the motor is capable, a smaller motor on each machine will usually give better results. The choice between group drive and individual drive depends so entirely on local conditions that no specific rules can be given.

LOAD FACTOR

15. Load factor is the ratio of average load to maximum load; the term may be used in connection with a single motor or a whole plant in which many motors are operating. The average load, or power, is the total energy in kilowatt-hours used during a given period divided by the number of hours in the period. The maximum load may be considered as the motor rating in the case of a single motor, or the sum of all the motor ratings in a plant; or the maximum load may be measured by wattmeter or a maximum demand indicator. The

method requiring consideration of motor ratings is more common, because these ratings are easily read from the name plates; this method is less accurate, however, than that requiring actual measurement of maximum load.

Low load factor in an industrial plant indicates that some of the motors are standing idle, or possibly running with light loads part of the time. In very few plants is it possible to operate all the motors continuously at their full rated loads or at any constant load. For example, in most wood-working shops the machines are run only occasionally, and the load factor is sometimes as low as 5 per cent:

- 16. Knowledge of the load factor is of great value in estimating the quantity of energy required for a proposed motor installation. For example, if it is found that several motors aggregating 75 horsepower will be required to drive the machines in a planing mill that is to operate 10 hours per day, energy estimates based on 75 horsepower and 10 hours would be entirely too high. The load factor of many such plants is approximately 10 per cent., indicating that the average power requirement in this particular mill will probably be at the rate of only $75 \times .1 = 7\frac{1}{2}$ horsepower.
- 17. Load factors can be determined only by experience with many motor installations; these factors vary so widely for installations of any given nature that they must be used with great discretion. The busier a shop, the more nearly continuous will be the power requirement and the higher the load factor; hence, the load factor of any shop is higher at some seasons than at others.
- 18. The load factors in Table III are a guide in estimating the quantity of electric energy that will be required by motors in other similar industries. These load factors are average results obtained by observation in many plants; they are based on continuous operation, 8,760 hours (24×365) per year and on maximum load equal to the sum of the motor ratings. To use these factors in connection with a proposed installation of motors, estimate first the motor required for each machine or

TABLE III AVERAGE LOAD FACTORS

(From The Electrical Solicitors Handbook, National Electric Light Association)

Service	Load Factor Per Cent.	Service	Load Factor Per Cent
Bakeries	12	Laundries	20
Bed Mfg. (brass and iron)	20	Leather	8.5
Belt manufacturing	10	Lithographing	10
Blacksmith shop	15	Machine shops group	20
Roiler chan group	18	Machine shops, group Machine shops, individual	8
Boiler shop, group	8	Marble supps, marvidual	
Boiler shop, individual		Marble works, group	18
Bookbinders	9	Marble works, individual	10
Boots and shoes, group	25	Mattress manufacturing	6
Boots and shoes, individual	17	Newspapers, group	18
Bottling works	10	Newspapers, individual	8
Brass finishing	25	Ornamental iron works	17
Breweries	45	Paint manufacturing	25
Broom manufacturing	15	Packers	25
Brush manufacturing	7	Paper-box manufacturing.	18
Butchers, group	15	Pipe threading and cutting	8
Butchers, individual	9	Plumbing	20
Can Manufacturing	30	Pottery manufacturing	13
Candy Mfg., group	18	Printing (job) group	18
Candy manufacturing in-	10		
Candy manufacturing, in-	0	Printing (job) individual.	7
dividual	9	Printing (magazine)	20
Carpet cleaning	15	Refrigeration	50
Carpet weaving	17.5	Restaurants	20
Cement mixing	10	Rock crushing	18.5
Chemical works	II	Rubber manufacturing	9.5
Cigar boxes	6	Saw manufacturing	30
Clothing manufacturing	18	Screw manufacturing	30
Coffee roasting and grinding	7	Seed cleaners	18
Coopers	5.5	Sheet-metal works, group.	15
Creameries	20	Sheet-metal workers, indi-	
Diamond cutting and		vidual	10
polishing	13.5	Silversmiths	7
Dye works	15	Soap manufacturing	20
Electroplating	20	Spice-grinding group	12
	20	Spice-grinding, individual	8
Electrotypers	12	Stone working	6
Feather cleaners	-	Stone working	0
Feed grinders	6	Structural-steel manufac-	0.0
Fertilizer manufacturing	75	turing, group	20
Flour mills	23	Structural-steel manufac-	
Forge shops	10	turing, individual	12
Foundries, brass	6	Tannery	20
Foundries, group	15	Telephone stations	25
Foundries, individual	9	Textile mills	25
Glass grinding, polishing	17	Tinsmiths	10
Glove manufacturing	25	Tobacco	14
Glue manufacturing	15	Twine mills	₄₂ 30
Grain elevators	10	Wagon builders	5
Grocers, wholesale	15	Wall-paper manufacturing	12
Harness shops	10	Wheelwright	9
Hoisting and conveying	10	Woodworking, box making	10
	20	Woodworking, furniture.	28
Ice-cream manufacturing.			20
Ice making	30	Woodworking (general),	T Q
Ink making	23	group	18
Jewelry	15	Woodworking (general),	
Knitting mills	25 .	individual	6

each group of machines, multiply the sum of the motor ratings in horsepower by 746 to reduce to watts, the watts by 8,760, and this product by the load factor for that particular industry to give the probable energy output in watt-hours per year. This output must be divided by the average motor efficiency and by 1,000 to give the probable input in kilowatt-hours per year.

For example, suppose individual motor drive is to be installed in a general woodworking plant and that the sum of the ratings of all the motors is 50 horsepower. If all the motors were operated continuously at full rating, the energy required in a

year, 8,760 hours, would be $\frac{50\times746\times8,760}{1000} = \frac{326,748}{1000}$ kilowatt-1.000 e

hours, in which e is the average efficiency of all the motors. However, experience with similar plants has shown that only 6 per cent. of this energy will be required (load factor 6 per cent. from table); thus, if it is assumed that the average efficiency is 80 per cent., the probable annual energy requirement will be $.06 \times 326,748 = 24,506.1$ kilowatt-hours, an average of approx-

imately 2,042 kilowatt-hours per month.

FLYWHEELS

Mounting a heavy iron wheel, called a flywheel, on the shaft of a motor driving a fluctuating load lessens the maximum load on the motor and makes possible the use of a smaller motor than would be required without a flywheel. This statement applies only to motors driving loads that are subject to frequent and sudden changes; for example, some machine tools. The flywheel absorbs energy when the motor speed is high, as during times of light load, and gives it up when the motor slows down on account of heavy load, thus helping the motor carry the load peaks.

For best results, the motor speed must change considerably when the load changes, or, in other words, the speed regulation of the motor must be poor, in order to take advantage of the flywheel effect. This is the case with compound direct-current motors and with induction motors having high rotor resistance. Such motors are also capable of exerting the torque necessary to start the flywheel and accelerate its speed.

20. The design of flywheels is practically always based on service conditions and very seldom falls to the lot of an operating engineer. In order that the flywheel may be properly designed, the exact service conditions should be specified, including, if possible, a curve showing the load fluctuations. Sometimes a spare motor can be connected to a load temporarily and a graphic wattmeter used to obtain a record of the load conditions. Such instruments are described in another Section.

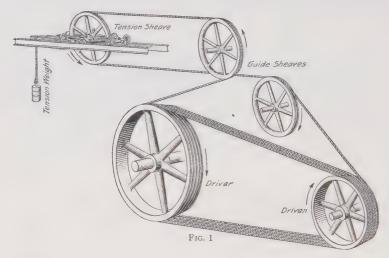
MECHANICAL CONNECTIONS

21. When the motor and its load are to rotate in the same direction and at the same speed, the connection may be made direct by coupling the motor shaft to the driven shaft or by using one continuous shaft carrying the rotating elements of both the motor and the driven machine. This drive is positive because no slippage can occur. When the direction of rotation or the speed of the motor and the driven machine differ, some form of indirect connection must be used, the chief forms being ropes, chains, belts, and gears.

ROPE DRIVE

- 22. Rope drive consists of one or more endless loops of rope running in grooves on the faces of pulleys, usually called sheaves. This drive is increasing in popularity, especially for power installations of 200 horsepower upwards. The advantages claimed for it over other forms of mechanical connections are: (1) ability to transmit energy for long distances and in any direction; (2) smooth and quiet running; (3) absence of electrical disturbance (belts generate static charges); (4) economy in first cost and in maintenance; and (5) practical absence of slip.
- 23. Rope drive is of two general classes, multiple and continuous. Multiple drive consists of several independent

loops of rope running side by side on the sheaves. Continuous drive consists of only one long loop of rope wrapped several times around the driving and driven sheaves, thus filling the grooves from one side of the sheaves to the other, whence the rope is returned over guide sheaves and an idler, called a tension sheave, to the opposite side again, as shown in Fig. 1. The tension sheave is usually arranged to travel a limited distance so as to take up the slack as the rope stretches. There are several ways of arranging the tension sheave other than the way shown in Fig. 1.



- **24.** Transmission ropes are made of wire, of cotton fiber, and of manila fiber. Wire rope is suitable for transmitting large quantities of energy long distances where the rope is subjected to few turns around pulleys, as in cable railways. Cotton rope is suitable for comparatively small transmission systems over small sheaves, but manila rope is best for the great majority of rope transmissions because of its superior strength and durability.
- 25. Manila Transmission Rope.—The information in Table IV can be used in selecting manila-rope sizes and speeds and sheave diameters. The power that each rope can transmit

CAPACITY OF EACH MANILA TRANSMISSION ROPE WITH 180 DEGREES ARC OF CONTACT TABLE IV

Diameter of Rope Inches	1,500	2,000	2,500	Speed c	of Rope, ii	Speed of Rope, in Feet per Minute 5,000 3,500 4,000 4,500	Minute 4,500	2,000	9,000	2,000	Minimum Di- ameter Smallest Sheave Inches
					Horsepower	wer					
7[2	1.45	6.I	2.3	2.7	3.0	3.2	3.4	3.4	3.1	2.2	20
ro 00	2.3	3.2	3.6	4.2	4.6	5.0	5.3	5.3	4.9	3.4	25
හ]4 1	3.3	4.3	5.2	5.8	6.7	7.2	7.7	7.7	7.1	4.9	30
r-[00	4.5	5.9	7.0	8.2	1.6	8.6	10.8	10.7	9.3	6.9	36
I	5.8	7.7	9.2	10.7	6.11	12.8	13.6	13.7	12.5	00	42
14	9.2	12.1	14.3	16.8	18.6	20.0	21.2	21.4	19.5	13.8	54
13	13.I	17.4	20.7	23.I	26.8	28.8	30.6	30.8	28.2	8.61	09
I 3	18.0	23.7	28.2	32.8	36.4	39.2	41.5	41.8	37.4	27.6	72
2	23.I	30.8	36.8	42.8	47.6	51.2	54.4	54.8	50	35.2	84

increases at increased speed up to 4,500 or 5,000 feet per minute, beyond which the power decreases owing to the effect of centrifugal force and air resistance. In general, the rope speed for maximum economy should be from 4,000 to 4,500 feet per minute. Large sheaves with few ropes, or few turns of rope, are usually preferable to smaller sheaves and more ropes. Ropes having a diameter greater than $1\frac{3}{4}$ inches are seldom used except in very large transmissions, say 1,000 horsepower and more.

CHAIN DRIVE

26. Chain drive consists of an endless chain running over sprocket wheels, as on a bicycle. The links are made to fit accurately over the sprockets, so that no slipping can occur. The speed of each sprocket wheel is inversely proportional to its diameter or to its number of teeth.

Let s = speed of motor sprocket; d = diameter of motor sprocket; t = number of teeth in motor sprocket; S = speed of driven sprocket; D = diameter of driven sprocket; T = number of teeth in driven sprocket.

Then, $\frac{s}{S} = \frac{D}{d} = \frac{T}{t}$

For example, a motor running at 1,000 revolutions per minute can be used to drive a machine at 100 revolutions per minute by using a 3-inch sprocket on the motor shaft and a 30-inch sprocket on the driven shaft of the machine, because $\frac{1,000}{100} = \frac{30}{3}$.

Chain drive is useful for large speed reductions between close centers. It is sometimes preferable to gear drive on account of being more quiet in operation.

BELT DRIVE

27. Belt drive is probably the most common method of connecting motors to their loads, especially motors of small and medium sizes. In order to use it, the distance between the driving and the driven shafts must be enough to allow some belt sag, and the slack side should be above, as indicated in

Fig. 2, so that the belt will more fully wrap and cling to the pulleys. One pulley should never belocated directly over the



other if avoidable; for best results, the angle between the horizontal and a line connecting the two pulley centers should not exceed 45°. Some provision is generally necessary for adjusting the belt tension. This provision is usually a screw device for sliding the motor on rails, but in some cases idler pulleys are pressed against the slack side of the belt, as indicated at I, Fig. 2, by a spring or by a weight.

28. Calculations.—In a belting problem, the speed of the machine to be driven is generally known, and pulleys should be selected so as to allow the highest practicable motor speed, in order to reduce the motor cost.

Let d = diameter of motor pulley; s = speed of motor pulley; D = diameter of driven pulley;S = speed of driven pulley.

Then, $\frac{d}{D} = \frac{3}{3}$

If the speed S of the driven machine is the only known value, the other three can be chosen within the limits of good engineering practice. For example, if the machine must run at 250 revolutions per minute and its pulley is 20 inches in diameter, S and D in the foregoing formula are fixed. If a motor running at 1,150 revolutions per minute is available, then $\frac{d}{d} = \frac{250}{2}$ and

d=4.35 inches. As pulleys with fractional diameters smaller than $\frac{1}{2}$ inch are rarely used, a $4\frac{1}{2}$ -inch pulley would probably be selected in this case, giving a machine speed $S=\frac{4\frac{1}{2}\times 1,150}{20}$

= 258.75 revolutions per minute. If the machine speed is desired more nearly 250 revolutions per minute, use may be made of a $4\frac{1}{2}$ -inch motor pulley and a 21-inch machine pulley, which give 247 revolutions per minute, or a 5-inch motor pulley and a 23-inch machine pulley, which give 250 revolutions per minute. If a cheaper motor is desired, a 4-inch motor pulley and a 28-inch machine pulley would allow a motor speed of 1,750 revolutions 4 250

per minute because
$$\frac{4}{28} = \frac{250}{1,750}$$
.

29. The power that a belt can transmit safely depends on its speed, its thickness, its width, on the arc of contact between the belt and the smaller pulley, and on the material of which the belt and the pulley are made.

The belt speed is the rate at which any point on the belt moves; this rate is the product of the circumference of either pulley and the number of revolutions of the pulley per minute. With the letters d, D, s, and S representing the same quantities as in Art. 28,

belt speed in feet per minute =
$$\frac{\pi ds}{12} = \frac{\pi DS}{12}$$

30. Best results are usually obtained with belt speeds between 3,000 and 5,000 feet per minute; speeds above 5,500 feet per minute are not good practice. For example, if the driven pulley must run at 500 revolutions per minute and a belt speed of approximately 4,500 feet per minute is desired, substitution of these values in the formula gives

$$4,500 = \frac{\pi}{12} \frac{D \times 500}{12}$$
, or $D = \frac{12 \times 4,500}{500 \pi} = 34$ inches, approx.

A 34-inch pulley would give 4,450 feet per minute, and a 36-inch pulley 4,712 feet per minute; either pulley; or even a 38-inch pulley giving nearly 5,000 feet per minute, would be good practice.

- **31.** Belt thickness is specified as single, double, and triple. The transmitting capacity of belts is sometimes expressed in speed per minute at which 1 horsepower per inch width can be carried. This speed is approximately as follows: For single belts, 900; for double belts, 450; and for triple belts, 350. The capacity is directly proportional to the speed and the width; thus a 4-inch single belt running at 4,500 feet per minute can transmit $4,500 \div 900 = 5$ horsepower per inch width or $4 \times 5 = 20$ horsepower total.
- 32. The arc of contact of the belt with the smaller pulley is the only one that need be considered, since the belt will not slip on the larger pulley. This arc depends on the difference between the diameters of the two pulleys and on the distance between pulley centers. If the pulleys have equal diameters, the belt will wrap approximately one-half of each pulley surface, or the arc of contact will be 180°. In any case, the arc of contact for the small pulley can be found by the formula

$$arc = 180^{\circ} - 2 \sin^{-1} \frac{D - d}{24 L}$$

in which d = diameter of small pulley, in inches;

D = diameter of large pulley, in inches;

L = distance between pulley centers, in feet.

The expression $2 \sin^{-1} \frac{D-d}{24 L}$ means two times the angle whose

sine is $\frac{D-d}{24L}$. After the value $\frac{D-d}{24L}$ has been determined,

the corresponding angle can be found in the Table of Natural Sines, Cosines, Tangents, and Cotangents accompanying *Trigonometry and Graphs*. Approximate results are sufficiently accurate for practical purposes.

 $\label{eq:example.} \textbf{Example.} \textbf{—} \textbf{Find the arc of contact of a belt on a 10-inch pulley belted} \\ \textbf{to a 32-inch pulley with a distance of 12 feet between pulley centers.}$

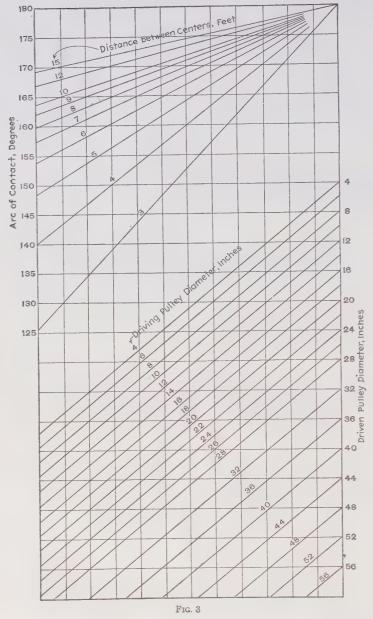
SOLUTION.—According to the formula,

arc =
$$180^{\circ} - 2 \sin^{-1} \frac{32 - 10}{24 \times 12} = 180^{\circ} - 2 \sin^{-1} .0764$$

From the table of natural sines and cosines, .0764 is the sine of 4° 23' and $2\times4^{\circ}$ 23' = 8° 46'; then,

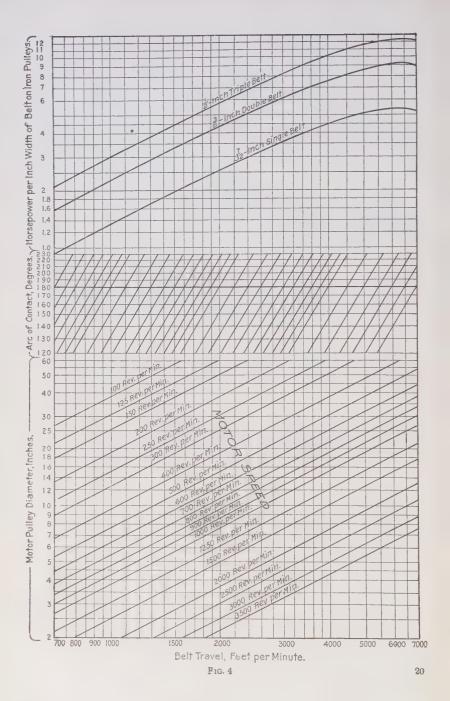
$$arc = 180^{\circ} - 8^{\circ} \ 46' = 171^{\circ} \ 14'$$
. Ans.

§ 38



- 33. Fig. 3 shows a chart by means of which the arc of contact of a belt on the smaller of two pulleys can be readily determined when the pulley diameters and their distance apart are known. For example, to determine the arc of contact on a 10-inch pulley belted to a 32-inch pulley with 12 feet between pulley centers, find 32 on the right-hand margin and horizontally to the left find a point on the oblique line representing a 10-inch driving pulley; vertically above this point find a point on the oblique line representing 12 feet between centers, and horizontally to the left of this latter point find on the margin the value of the arc of contact, approximately 171°. This chart is accurate enough for practical purposes and includes data for the pulleys in most common use.
- 34. Fig. 4 shows a chart representing the interrelations of pulley diameter, motor speed, belt travel, arc of contact, and horsepower per inch width of leather belt for different belt thicknesses on iron pulleys. This chart is based on the figures previously given herein, and belts selected by it will conform to established practice. For paper pulleys, add 30 per cent. to the horsepower values given by the chart. For four-ply canvas or rubber belt, use the value for single leather belt. The use of the chart is best explained by an example.

Assume that 10 horsepower is to be transmitted from a 10-inch pulley running at 1,000 revolutions per minute, by a single leather belt with an arc of contact of 170°. To determine the width of belt required, first find the pulley diameter 10 on the lower left-hand margin of Fig. 4 and horizontally to the right find a point on the oblique line marked 1,000 R.P.M. From this point proceed vertically upwards to the horizontal line near the center of the chart representing 180° arc of contact, thence follow the oblique line downwards to the horizontal line representing 170° arc of contact, then vertically upwards to the oblique line marked $\frac{7}{32}$ -inch single belt, and then horizontally to the left, where approximately 3.1 horsepower per inch width of belt is found. For 10 horsepower, the belt must be $10 \div 3.1$, or slightly over 3 inches wide; a 4-inch belt would probably be used. The width of the pulley faces should be a little greater

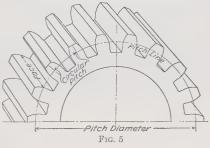


than the width of the belt; a 5-inch pulley face would do here, though a 6-inch face would be better because it would allow 1 inch play of belt each way.

SPUR-GEAR DRIVE

- 35. When a motor and its driven machine operating at different speeds are mounted close together, spur gearing is often the best method of mechanical connection. A pinion on the motor shaft meshing with a gear-wheel on the driven shaft makes positive connection, and the ratio of speed reduction can be made high.
- **36.** Fig. 5 shows most of the features of importance to consider in selecting gears. Two geared wheels running together

have the same effect as would two smooth cylinders running together by friction only and without slipping. Such cylinders are called *pitch cylinders* and are represented on drawings of gear-wheels by the *pitch line*, which is the circumference of the *pitch*



circle. The circular pitch is the distance along the pitch line between the centers of adjacent teeth. The pitch diameter is the diameter of the pitch circle; reference to the diameter of a pinion or gear always means pitch diameter unless otherwise specified. The face is the length of teeth parallel to the shaft. The diametral pitch is the number of teeth per inch of diameter. or the ratio of the number of teeth to the diameter in inches; for example, a 20-tooth pinion 5 inches in diameter has a diametral pitch of $20 \div 5 = 4$.

37. Calculations.—The most important relations to be considered in gearing calculations may be expressed by means of formulas.

Let r = number of revolutions per minute of pinion;

R=number of revolutions per minute of gear;

d = pitch diameter, in inches, of pinion;

D = pitch diameter, in inches, of gear;

n = number of teeth in pinion;

N = number of teeth in gear;

p = diametral pitch of both pinion and gear;

 p_1 = circular pitch of both pinion and gear;

L =distance, in inches, between shaft centers;

o = gear ratio, or ratio of speeds;

S = pitch line speed, in feet per minute.

Then,
$$o = \frac{N}{n} = \frac{D}{d}$$
 (1)
$$L = \frac{d+D}{2}$$
 (2)
$$p = \frac{n}{d} = \frac{N}{D}$$
 (3)
$$p_1 = \frac{\pi d}{n} = \frac{\pi D}{N} = \frac{\pi}{p}$$
 (4)
$$S = \frac{\pi d r}{12} = \frac{\pi D R}{12}$$
 (5)

If the gear ratio and the number of teeth in either wheel or the diameter of either wheel are known, the corresponding number for the other wheel can be found by formula 1. For example, if the gear ratio is 6 and the pinion has 22 teeth, the gear must have $6\times22=132$ teeth $(N=o\ n)$; if the pinion in this case is $2\frac{3}{4}$ inches in pitch diameter, the gear must be $6\times2\frac{3}{4}=16\frac{1}{2}$ inches diameter $(D=o\ d)$.

In the problem just assumed, the distance L between shaft centers must be $\frac{16\frac{1}{2}+2\frac{3}{4}}{2}=9\frac{5}{8}$ inches, according to formula 2; the diametral pitch p is $22\div2\frac{3}{4}$ or $132\div16\frac{1}{2}=8$, according to formula 3; the circular pitch p_1 is $\frac{3.1416}{8}=.3927$ inch, according to formula 4, and the pitch line speed S, is $\frac{3.1416\times2\frac{3}{4}}{12}r$ or

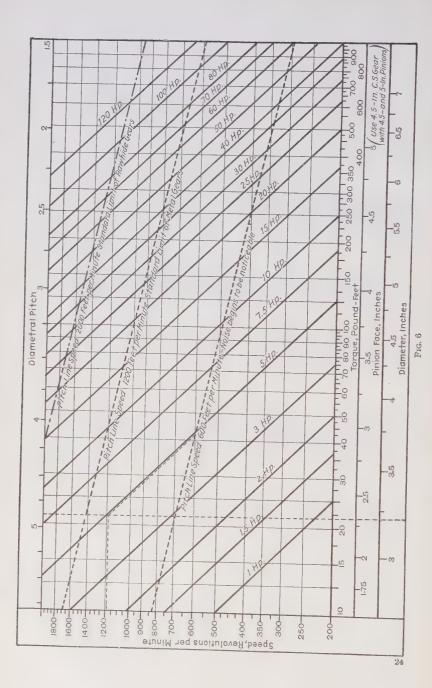
 $\frac{3.1416 \times 16\frac{1}{2}}{12}$ R, according to formula 5. The pitch line speed in feet per minute can thus be determined as soon as x or R is

in feet per minute can thus be determined as soon as r or R is known.

38. For satisfactory service in most applications, motor gears should be strong, durable, and quiet in operation. The first two of these requirements, and to some extent the third, are attained by selecting a pinion with the proper face, diameter, and diametral pitch. Gears selected in accordance with the chart, shown in Fig. 6, will meet all ordinary requirements. This chart is based on the use of gear dimensions directly proportional to the motor torque, that is, to the strength required, and gives proper dimensions for steel pinions; the face of a rawhide pinion should be 25 per cent. longer than that of a steel pinion for the same work.

To illustrate the use of the chart, assume that a pinion is required for a 5-horsepower motor running at 1,200 revolutions per minute. Find the intersection of the oblique line marked 5 H.P. with the horizontal line representing 1,200 revolutions per minute, and vertically under this intersection near the lower edge of the chart find approximately 22 pound-feet torque (pounds at 1 foot radius), 2.3-inch pinion face, and 3.2-inch pitch diameter; on the same vertical line at the top of the chart find the diametral pitch 4.85. The figures cannot always be used exactly as given in the chart, because some of the fractional dimensions are impracticable. Fractional face dimensions smaller than $\frac{1}{4}$ inch are seldom used, and in the example just given a 24-inch face would be good practice. The diametral pitch for small pinions is usually a whole number, and in this case a pitch of 5 would probably be used: the pitch diameter can remain 3.2, as given by the chart, because the number of teeth will then be $5 \times 3.2 = 16$.

For motors in very heavy service, such as that for which series motors, heavily compounded motors, and slip-ring induction motors are frequently employed, the pinion face as found by the chart should be increased approximately 50 per cent. in order to give the required strength.



- **39.** Gears.—With steel pinions, the gear face is usually the same as the pinion face, and the material is generally cast iron for light and medium heavy service. The diametral pitch and circular pitch are necessarily the same for both gear and pinion in order to make them mesh properly; the gear ratio being known, the gear diameter depends on the pinion diameter in accordance with formula 1, Art. 37, in which D=od. Cast, steel is much stronger than cast iron and is frequently used for gears where the face of a cast-iron gear would be $4\frac{1}{2}$ inches or more.
- 40. Noise.—An objection to gears for many applications is their noisy operation. This noise is caused by vibration and is least when the pitch-line speed is low, also when the foundation of the motor and the driven machine is firm and rigid, and when the pinion is mounted close to the motor bearing. An additional bearing outside the pinion lessens vibration and noise, and is a necessity with large motors or in heavy service. The noise comes mostly from the gear-wheel; the pitch of this noise is higher and its penetrating power greater with a large number of fine teeth than with fewer and coarser teeth.

With steel pinions and cast-iron gears, noise is not usually objectionable at pitch-line speeds below 1,200 feet per minute. With rawhide pinions, this limit can be made, 2,000 or sometimes 3,000 feet per minute without serious noise; for best results, the gear should come in contact with only the rawhide and not with the metal flanges of the pinion.

WOODWORKING

41. Woodworking machinery usually operates at fairly high speed and at constant speed. The starting conditions are not hard, except in the larger machines with considerable friction. The motors must be capable of operating in the midst of dust and shavings without great increase of fire hazard.

Squirrel-cage induction motors are best suited to this work on account of constant-speed characteristics and absence of sliding contacts. Shunt-wound direct-current motors are also used, but they must usually be in entirely enclosed frames or in rooms separate from the driven machines. For starting the heavier woodworking machines, compound motors are sometimes preferable.

42. Power Required.—The power to drive any woodworking machine depends on the kind of wood to be worked, the rate of feed, the condition of the cutting tools, and the condition of the bearings and gears in the machine. For belt drive, the motor speed must not be too high to permit the use of a pulley of ample size, especially for a machine that has high static friction and is hard to start. In starting such a machine, the belt would be thrown off a pulley that is too small; moreover, the dry, dusty conditions in woodworking shops decrease the adhesion between pulleys and belts and necessitate liberal belt and pulley sizes.

No practicable method exists for calculating the power required to drive woodworking machinery; experimental data are essential in practically every case. Manufacturers of woodworking machines and of motors can always furnish estimates based on experiments, but conditions of application may vary enough to make these estimates inaccurate in some cases.

MACHINE TOOLS

43. Types of Motors Required.—Direct-current motors are best suited to the operation of machine tools requiring adjustable speed. A tool required to handle miscellaneous work with pieces of varying size and material must operate at different speeds for maximum economy. For example, in turning a piece, the lathe speed must be increased as the diameter of the work decreases in order to keep the cutting speed fairly constant; shunt motors are preferable for such applications. For machines having heavy parts to start or many bearings that make the friction high, compound motors are preferable; such motors should also generally be used on punch presses, shears, bending rolls, and similar machines where the torque is excessive for brief intervals.

Alternating-current induction motors are also much used for constant-speed machine-tool service, squirrel-cage motors where the starting conditions are comparatively easy, and slipring motors for machines that start hard. Induction motors with high secondary resistance are applicable in some cases where starting conditions or intermittent operating conditions are hard, provided good speed regulation is not essential.

Open-type motors are satisfactory in many cases, but if tools, chips, or loose materials of any kind are likely to get inside the motor, it should be semi-enclosed or fully inclosed, according to the nature of the substances to be excluded. Semi-enclosed motors are very frequently used for machine-tool applications.

With few exceptions, the motors for driving machine tools have horizontal shafts and are belted, coupled, or geared to the driven shaft of the tool. Chain drive is sometimes employed in preference to belts or gears when the center distance is small and the ratio of speed reduction large. Back gears and countershafts also are sometimes used, though ordinarily most of the speed reduction is provided for on the tool itself.

Machine-tool motors are rated for intermittent service, one or two hours at rated load with temperature rises within safe limits. Continuous operation of machine tools at steady loads during long continued periods is usually impracticable.

44. Motor Selection.—Each motor should be selected for the average power requirement, provided the maximum requirement, which usually occurs during the first, or *roughing*, cut does not exceed the overload capacity for which the motor is recommended. The duration of cut and the number of cuts in a given time must be considered in making the selection.

In general, the power required to drive a machine tool depends on three conditions: (1) The type and condition of the cutting tool employed; (2) the rate of removing metal; and (3) the kind of metal that is being cut.

45. All cutting tools employed on machine tools may be classified in three groups: (1) chisel-type tools used on lathes, boring mills, planers, and shapers; (2) drills and reamers; and (3) milling cutters.

46. Calculations.—The rate of removing metal in cubic inches per minute is the product of the cutting speed in inches per minute and the area of a cross-section of the cut in square inches. With tools of the first group, this area is the product of the depth of cut in inches and the feed, or width, of cut. If the area of cut and the cutting speed are known, the quantity of metal removed per minute can be readily determined by the aid of Fig. 7.

For example, suppose a cut $\frac{1}{4}$ inch deep with $\frac{1}{16}$ -inch feed is being taken in a lathe on a steel shaft 3 inches in diameter rotating at 75 revolutions per minute. The area of cut is $\frac{1}{4} \times \frac{1}{16} = \frac{1}{64}$, or .0156 square inch approximately, or for practical purposes

.016. The cutting speed is $\frac{3\pi}{12} \times 75 = 59$ feet per minute. A

horizontal line from the number .015 on the left margin meets a vertical line from the number 60 on the lower margin at a point about central between the oblique lines marked 11 and 12, indicating that approximately 11.5 cubic inches of metal are removed per minute.

47. The rate at which a drill removes metal may be calculated by means of the formula

$$Q = .7854 \ d^2 f$$
,

in which Q = cubic inches per minute; d = diameter of hole, in inches; f = rate of feed, in inches per minute.

A milling machine removes metal at a rate equal to the product of the length and depth of cut in inches and the feed

in inches per minute.

48. The approximate horsepower for machine tools is equal to the product of the cubic inches of metal removed per minute and a constant; that is,

$$H. P. = CQ$$

With chisel type tools, the constant C is from .3 to .5 for cast iron, .6 for wrought iron and machinery steel, 1 to 1.25 for steel .5 per cent. carbon and harder, and .2 to .25 for brass and similar alloys. With drills, these constants should

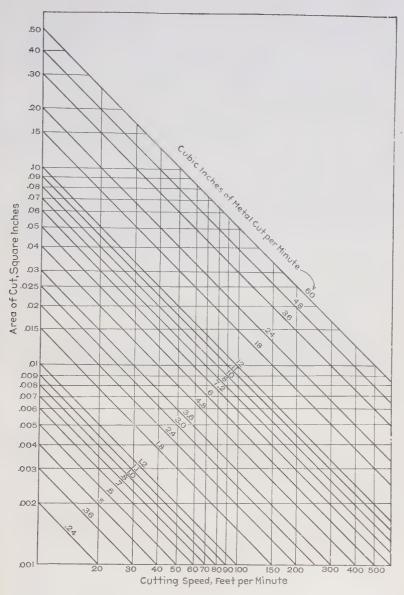


Fig. 7

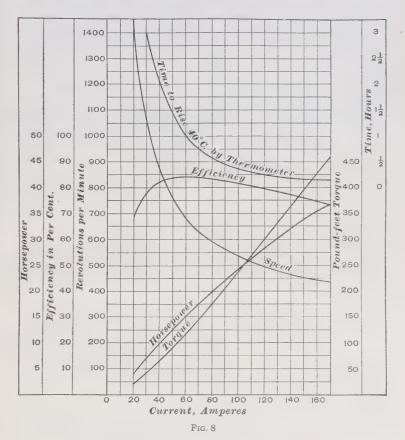
be doubled. Vertical milling machines require approximately 1 horsepower and horizontal machines 1.6 horsepower per cubic inch of metal cut per minute. Small tools for light work or finishing require only enough power to start the machine and overcome its friction while running; usually $\frac{1}{2}$, 1, or 2 horsepower is sufficient, according to the size of the machine.

For example, the lathe referred to in Art. 46 while removing 11 cubic inches from a steel shaft requires approximately $.6\times11=6.6$ horsepower. For cutting hard steel at the same rate, the maximum requirement would probably be $1.25\times11=13.75$ horsepower.

CRANES AND HOISTS

- 49. Specially constructed series-wound direct-current motors are most suitable for crane and hoist service, although special slip-ring motors are successfully used in some cases. The motor frames must be very heavy, substantial, and compact. The weight and substantial construction are necessary to resist the heavy stresses, and compactness is required for the limited space available for installing motors. The electrical design must be such that excessively heavy torque can be exerted for brief intervals, as is possible with series motors; if the friction load of a hoist is very light, the motor should also have enough shunt-field winding to prevent excessive speed when running idle.
- 50. Motor Characteristics.—The performance curves of a motor must be known before it can be applied intelligently to crane or hoist service. Fig. 8 shows curves of a 220-volt hoist motor by means of which the performance of the motor under any set of conditions can be foretold. For example, suppose a torque of 175 pounds at 1 foot radius, or 175 pound-feet, is required to operate a hoist. The performance of the motor with that torque is found by following the horizontal line corresponding to 175 pound-feet, as indicated on the right margin, until this line intersects the curve indicating torque. Then follow the vertical line through this intersection to the lower margin, finding 80 amperes, also upwards to its intersections

with the curves indicating horsepower, speed, efficiency, and time-temperature. From these intersections trace horizontally to the left margin for values of horsepower 20, speed 590 revolutions per minute and efficiency 83.5 per cent., and to the right for the time, approximately 35 minutes, during which the



motor can carry this load without showing a temperature rise higher than 40° C. in any part.

If this speed is too slow or if any other characteristic thus found is unsatisfactory, another motor must be selected. Torque and speed are the important characteristics of such motors; rating them in horsepower is of little use for making selections. For example, the motor with performance indicated in Fig. 8 could develop a torque of 400 pound-feet with the following approximate characteristics, as shown by the curves: amperes, 150; horsepower, 34; speed, 450 revolutions per minute; efficiency, 76 per cent.; and time to rise 40° C., about 10 minutes.

PUMPS

- 51. The operation of pumps is an ideal application for electric motors, both direct current and alternating current. The load can be accurately calculated, the motor can be selected to operate at its most efficient load, and a pump load is usually continuous for considerable periods. The time of operation can often be selected when the power station is not fully loaded, and energy can therefore be supplied at reduced cost. A motor-driven pump can be located at the most advantageous position and operated from a distant point more convenient for an attendant, or it can be arranged for automatic operation resulting from the rise and fall of a float or the movements of the indicator of a pressure gauge.
- 52. Classes.—Pumps may be classed as piston, plunger, centrifugal, rotary, and screw types. In a piston pump, the piston carrying packing plays inside a cylinder. In a plunger pump, the plunger plays inside a cylinder with stationary packing rings. In both piston and plunger pumps, valves prevent movement of the liquid in the wrong direction, and the discharge is pulsating. By means of an air chamber the pulsations can be smoothed out into a steady stream, as from high-pressure fire pumps.

In a centrifugal pump, a rotating element, called an *impeller*, consisting of a series of blades, or vanes, sets the liquid in motion inside the fan casing, and stationary vanes guide this motion in the desired direction. The discharge is steady, or non-pulsating. In a rotary pump, the impeller consists of a series of chambers, or buckets, each of which impounds a

quantity of liquid and forces it through the discharge outlet, the action being so rapid that the discharge is a steady stream. In a screw pump, the blades are in the form of a spiral that, in turning, forces the material forwards.

- 53. Piston, plunger, rotary, and screw pumps are positive in action and are suitable for working against high pressures; screw pumps are especially suitable for handling semiliquid masses containing coarse particles not too large to pass between the blades. In general, centrifugal pumps are best suited for handling large quantities of liquid or semiliquid at comparatively low pressures, although pumps of this class are also made for operating at high pressures.
- **54.** Pump Data.—The following information is approximately correct. One gallon (U. S.) of water contains 231 cubic inches and 1 cubic foot contains $7\frac{1}{2}$ gallons. Fresh water weighs $8\frac{1}{3}$ pounds per gallon, or $62\frac{1}{2}$ pounds per cubic foot; seawater weighs $64\frac{1}{8}$ pounds per cubic foot.

Atmospheric pressure at sea level is 14.7 pounds per square inch. In a perfect vacuum, this pressure supports a column of mercury 29.9 inches high and a column of water 33.9 feet high. If a long tube, open at one end, is filled with mercury (quick-silver), inverted, and the open end placed under the surface of mercury in an open vessel without allowing any mercury to escape from the tube while inverting it, the column of mercury in the tube will remain standing 29.9 inches high. The pressure of the atmosphere on the surface of the mercury in the open vessel is 14.7 pounds per square inch, and this pressure holds the mercury up in the tube. In a longer tube filled with water and placed upright with the open end under the surface of water in an open vessel the column of water will stand 33.9 feet high owing to the same cause.

In pumping problems, the height of liquid is called the *head*. The pressure per square inch on the lower face of 1 cubic foot of pure water is $62.5 \div 144 = .434$ pound. The pressure per square inch at the foot of *any column of pure water of any cross-sectional area* is .434 multiplied by the head in feet. Conversely, the head

equals the pressure per square inch divided by .434 or multiplied by 2.3; or, expressed as formulas,

$$p = .434h$$
 (1)

$$h = 2.3 p,$$
 (2)

in which p = pressure in pounds per square inch; h = head, in feet.

55. The velocity of water in a pipe may be calculated by

the formula

$$v = \frac{.408 \, Q}{d^2},$$

in which v = velocity, in feet per second;

Q=rate of discharge, in gallons per minute;

d =interior diameter of pipe in inches.

For example, if 700 gallons per minute is discharged from a 4-inch pipe, the velocity of the liquid in the pipe is

$$v = \frac{.408 \times 700}{4 \times 4} = 17.85$$
 feet per second

Any one of the three quantities represented by letters in the foregoing formula can be found if the other two are known. For example, to carry 750 gallons per minute at a velocity of 8 feet per second, the size of pipe is calculated as follows:

$$8 = \frac{.408 \times 750}{d^2}$$

$$d = \sqrt{\frac{.408 \times 750}{8}} = \sqrt{38.25} = 6.18$$
 inches, diameter

In practice, a standard 6-inch pipe would probably be used in this case, making the velocity $v = \frac{.408 \times 750}{6 \times 6} = 8.5$ feet per second.

56. The weight of water in a pipe is $1.022 \, d^2$ pounds per yard, or the weight in pounds in each yard of pipe is approximately equal to the square of the diameter in inches.

57. The power required to drive a pump can be calculated by the formula:

H. P. = $\frac{Qh}{3,960e}$

or, approximately, $\frac{Qh}{4,000e} = \frac{25Qh}{10^5e},$

in which H. P. = horsepower;

Q = gallons per minute;

h = head, in feet;

e = efficiency of the pump expressed decimally.

For estimating purposes, the efficiencies of triplex plunger pumps may be assumed at .60 to .85; those of centrifugal pumps at .35 to .75; and those of rotary pumps at .60 to .80.

EXAMPLE.—Find the horsepower required to pump 700 gallons per minute against a head of 35 feet with a centrifugal pump operating at 60 per cent. efficiency.

SOLUTION.—By substituting values in the formula, it is found that

H. P. =
$$\frac{25 \times 700 \times 35}{10^{5} \times .6}$$
 = 10.2, approx.

- 58. Head of Liquids.—In calculating the power required for pumping, suction head, discharge head, and friction head must be combined to give the total head. Suction head is the vertical distance from the lower level of the liquid to the pump center; discharge head is the vertical distance from the pump center to the upper level, and friction head is the vertical head equivalent to the loss of pressure due to movement of the liquid through the pipes. The suction head and the discharge head together is the actual lift, or rise, of liquid. Friction head depends on the square of the velocity in the pipe, the length of pipe, and the conditions affecting freedom of flow, as elbows, bends, valves, and roughness of pipe interior. To obtain low friction head, the pipe should be ample in size, the interior smooth, and the number of sharp turns and valves small.
- 59. Table V gives friction head per hundred feet at a single rate of flow in each pipe. The friction head in a pipe at any other rate of flow and for any length of pipe can be calculated from the values given in the table.

Let h_1 =friction head to be calculated at Q_1 gallons per minute;

l=length of pipe in hundred feet;

h=friction head at Q gallons per minute, both given in Table V.

Then,

$$h_1 = l h \frac{Q^2_1}{Q^2}$$

TABLE V
FRICTION HEAD OF WATER IN STRAIGHT CLEAN WROUGHTIRON PIPE

Inside Diameter Inches (d)	Gallons per Minute (Q)	Friction Head per 100 Feet (h)	Inside Diameter Inches (d)	Gallons per Minute (Q)	Friction Head per 100 Feet (h)
34	10	29.900	10	1,600	1.822
I	20 .	28.290	12	2,000	1.150
$I\frac{1}{4}$	30	21.040	14	2,500	.835
$I\frac{1}{2}$	50	23.000	16	3,000	.619
2	100	21.750	18	4,000	.609
$2\frac{1}{2}$	150	16.100	20	5,000	.562
3	200	11.540	24	7,000	.443
4	300	6.220	.30	10,000	.298
5	400	4.252	36	15,000	.269
6	600	3.289	42	18,000	.207
8	1,000	2.174	48	20,000	.120

For example, 400 gallons per minute in a straight, clean, wrought-iron pipe, 6 inches in diameter and 1,500 (15 hundred) feet long will cause a friction head

$$h_1 = 15 \times 3.289 \times \frac{400^2}{600^2} = 21.9$$
 feet,

3.289 being the value per hundred feet for 600 gallons per minute in a 6-inch pipe, as given in Table V.

60. Fittings can be calculated as additional straight pipe according to Table VI. Unless the fittings are reamed out

smooth after machining, the values given in this table should be multiplied by 2. For example, two elbows and two globe valves in a 6-inch pipe line are equivalent to $2\times26+2\times50=152$ feet

TABLE VI
FEET OF STRAIGHT PIPE EQUIVALENT TO PIPE FITTINGS

Style of Fitting		Size of Fitting, Inches									
Style of Fitting	34	I	I 4	1 1 2	2	2 1 2	3	1	5	6	
Elbows	5	5	6	7	7	10	12	18	25	26	
Return bends	10	10	12	14	14	20	24	36	50	60	
Globe valves	6	6	7	8	8	12	24	30	40	50	

of straight pipe, provided the fittings are reamed out smooth, or 304 feet if left rough. If these fittings are included in the pipe assumed in Art. 59, the length should be increased to 1,652 or to 1,804, according to the conditions of the fittings, making l in the solution either 16.5 or 18 instead of 15.

FANS, BLOWERS, AND EXHAUSTERS

- 61. An important application for electric motors is to drive devices for moving air and gas. The volume, pressure, and velocity of delivery of the gases, as well as the construction of blowers and exhausters, vary so widely that the power required in any given case is better obtained from experiment or from the manufacturers of such devices. Any fan may be called a blower if it forces air or gas into a chamber or system and an exhauster if it withdraws air or gas.
- 62. A centrifugal fan has an axial intake and a radial, or tangential, delivery. A centrifugal blower usually receives from both sides, while an exhauster may receive from one side only, this inlet being connected with the system from which air or gas is taken. Centrifugal fans are used for a great variety of purposes to move large volumes at pressures of a few ounces,

as for heating and ventilating, mechanical draft, removing dust, and poisonous gases, handling light materials, as grain and flour, etc. Restricting the inlet or outlet of these fans reduces the power required, provided the speed remains constant.

- 63. A disk fan both receives and delivers axially, causing a current of air or gas in the direction of the shaft. Disk fans are used almost entirely for ventilation and may operate as blowers or exhausters. The quantity of air moved and its velocity, rather than pressure, are the important considerations. Restricting the inlet or outlet of a disk fan operating at constant speed increases the power required.
- 64. A positive pressure blower is a rotary pump for air or gas. It delivers a fixed quantity per revolution, regardless of the pressure, giving the name positive. These blowers are used to move illuminating gas, air for blast furnaces, and for all purposes requiring gas or air at pressures ranging from a few ounces up to several pounds. Restricting the inlet or outlet very greatly increases the power required; if the restriction of the outlet is too great, the driving power will fail or some part of the system will burst on account of excessive pressure.

PERIODIC SERVICE

65. Motor ratings for service of a periodic nature, or a continually recurring cycle of operations, can be selected by the root-mean-square (R.M.S.) method. This method is based on the fact that heating in a motor is proportional to the square of the load and to the duration of the load. The square of each load during a complete cycle is multiplied by its duration, and the sum of these products is divided by the sum of the periods during the cycle; the square root of the quotient thus obtained is the horsepower rating of the motor for the cycle and for the whole time during which the cycle is to be repeated.

For example, suppose a motor must develop 20 horsepower for 5 seconds, then 30 horsepower for 15 seconds, then 10 horsepower 15 seconds, completing the cycle by running idle for 25 seconds, this cycle being repeated continuously for 2 hours.

The motor selected must, of course, be capable of developing the maximum output required, namely 30 horsepower, but a motor rated at 30 horsepower for 2 hours' service is much too large. The correct 2-hour rating is determined as follows:

$$20^{2} \times 5 = 2000$$

$$30^{2} \times 15 = 13500$$

$$10^{2} \times 15 = 1500$$

$$0^{2} \times 25 = 0$$

$$60 \quad)17000$$

$$283.33 + 0$$

 $\sqrt{283.33} = 16.83$, approximately.

A motor rated at 17 to 20 horsepower for 2 hours will probably answer the requirement, provided it is capable of developing 30 horsepower for 15 seconds in order to cover the maximum requirement.

66. A good example of periodic service is operating a shovel for unloading ore from a vessel. A large clam-shell bucket is closed in the ore, hoisted, the trolley, or car carrying the hoist, is run in over the dumping place, the bucket opened, the trolley run out again, and the bucket lowered into the ore to begin another cycle, these cycles to be repeated continuously for 5 hours. One motor operates the bucket and another the trolley. Assuming a set of conditions, the rating of the motor for the bucket can be determined as follows:

Assumed Conditions	Solution
Closing bucket 50 H. P. 8 sec	
Hoisting120 H. P. 10 sec	$120^2 \times 10 = 144,000$
Trolley in 0 H. P. 10 sec	$0^2 \times 10 = 0$
Opening bucket 20 H. P. 8 sec	$20^2 \times 8 = 3,200$
Trolley out 0 H. P. 10 sec	$0^2 \times 10 = 0$
Lowering and braking 50 H. P. 9 sec	$50^2 \times 9 = 22,500$
	55 189,700

 $\sqrt{189,700 \div 55} = \sqrt{3,450} = 59$ horsepower, nearly. The motor must be capable of developing this output under the assumed conditions for 5 hours and also a maximum output of 120 horsepower for 10 seconds.



STORAGE BATTERIES

INTRODUCTION

DEFINITIONS

- 1. Strictly, the contact surface across which electricity flows from a solid to a fluid is an **electrode**. Usually, however, the term *electrode* is applied to the solid itself. An electrode from which electricity flows into a fluid is an **anode**, or *positive electrode*; an electrode into which electricity flows from a fluid is a **cathode**, or *negative electrode*. A conducting liquid is an **electrolyte**.
- 2. A primary cell consists of two unlike electrodes immersed in an electrolyte, whereby an electromotive force is developed between the electrodes, and an electric current is set up when the electrodes are connected by an external conducting circuit. The direction of this current is from the anode to the cathode in the cell, and from the cathode to the anode in the external circuit; therefore, the positive terminal of a cell is connected to the cathode, or negative electrode, and the negative terminal to the anode, or positive electrode. This point should be remembered. The flow of electricity is accompanied by chemical changes, or reactions, within the cell: these alter the chemical composition of the electrodes and, usually, that of the electrolyte also. The quantity of material altered by the chemical reactions is proportional to the quantity of electricity, in ampere-hours, that flows through the circuit. When any of the materials entering

into the chemical reactions of a primary cell has been entirely altered, the cell is exhausted, or fully discharged.

3. The storage cell, secondary cell, or accumulator, as it is variously called, is fundamentally the same as a primary cell, but differs in that when discharged, either wholly or partly, the storage cell can be restored to its original state, or charged, by passing current through it for a sufficient length of time in the reverse direction. The material of the electrodes that undergoes chemical changes during charge and discharge, called the active material, is generally supported on the surface or in the openings, or pockets, of a conducting framework, called a grid. The grid with its active material is called a plate. Each electrode in a storage cell consists of a plate or of a group of plates connected in parallel. The plates of the positive electrode alternate with those of the negative, in order to provide the shortest path for the current through the electrolyte.

Two types of commercial storage cell are in use: the *lead-sulphuric-acid cell*, sometimes called, simply, the *lead cell*, and the *nickel-iron-alkaline cell*, known also as the *nickel-iron*, or *Edison*, *cell*. The names are derived from the chemical natures of the electrodes and electrolytes.

THEORY OF COMMERCIAL STORAGE CELLS

4. In the lead-sulphuric-acid cell, the grids, both positive and negative, are of lead or of lead-antimony alloy. The active material of the positive plate when the cell is fully charged is lead peroxide, a chemical compound of lead and oxygen. The active material of the fully charged negative plate is metallic lead in a spongy, porous state. The electrolyte is a solution of sulphuric acid, formed by mixing I part of pure concentrated acid with 2.5 parts, by weight (4.5 parts by volume), of distilled water. The specific gravity of the electrolyte—that is, the ratio of the weight of a given volume to that of an equal volume of water—is about 1.2.

The lead and the oxygen in lead peroxide are chemically combined into a substance from which neither can be separated except by a chemical process. The lead peroxide undergoes such a process during a discharge of the cell; half of the oxygen is transferred from the positive to the negative plate, producing lead monoxide, another chemical compound of lead and oxygen, on each plate. At the same time, the sulphuric acid is decomposed into water and a gas called sulphur trioxide: this gas combines with the lead monoxide, forming lead sulphate on each plate. The active material on each plate of a fully discharged lead cell is therefore lead sulphate; and the electrolyte has become weakened because of the presence of additional water formed by the decomposition of some of the sulphuric acid. Not all the sulphuric acid disappears from the solution, because, originally, more than enough acid was added to convert all the active material on the plates of the fully charged cell into lead sulphate. The excess of acid is necessary because pure water alone is a non-conductor.

During charge, the reactions are reversed: the acid is restored to the electrolyte; the active material of the positive plate is oxidized to lead peroxide, and that of the negative plate is reduced to spongy lead; and the chemical conditions of a fully charged cell are gradually reestablished.

It will be noted that the specific gravity (strength) of the electrolyte decreases during discharge and increases during charge, thereby furnishing an indication of the state of discharge of the cell.

5. In the fully charged nickel-iron cell, the active material of the positive plate is nickel peroxide, and that of the negative plate is finely divided metallic iron. The electrolyte is a dilute solution of potassium hydroxide, or caustic potash. A small quantity of lithium hydroxide is added to the electrolyte to improve the capacity of the cell.

During discharge, part of the oxygen of the nickel peroxide is dissociated and transferred to the negative plate, where it combines with the iron to form ferrous (iron) oxide; but the composition of the electrolyte remains unchanged. Unlike the electrolyte of the lead cell, the potassium hydroxide serves merely as a carrier of oxygen from one electrode to the other. When the cell is fully discharged, the active material of the positive plate is nickel oxide and that of the negative plate, ferrous oxide.

LEAD CELL

CONSTRUCTION OF THE LEAD CELL

FUNDAMENTAL TYPES OF PLATES

- **6.** Two fundamental, or general, types of plates have been developed for use in the lead cell; the $Plant\acute{e}$, or formed, plate, and the Faure, or pasted, plate.
- 7. The Planté plate, so called after its inventor, Gaston Planté, consists of a sheet or a grid of pure lead, usually ribbed or corrugated in order to increase the superficial area, upon the surface of which the active material is formed out of the metal of the plate by an electrolytic process. The original Planté process consisted in immersing the positive and negative plates in a bath of dilute sulphuric acid, passing current through the cell for a number of hours, then reversing the direction of current for a similar period, and repeating this cycle many times until sufficient active material was formed on the plate surfaces to give the desired capacity. This process, called forming, or formation, was too slow and expensive to be commercial. Later, it was found that by the addition of a small quantity of nitric acid to the electrolyte the forming process could be materially accelerated, and could be completed for positive plates without reversal. Modern negative Planté plates are produced by reversing positives; that is, by immersing them in an electrolyte of dilute sulphuric acid opposite dummy electrodes, and passing current through the electrolyte from the dummies to the plates until all the peroxide of lead in the plates is reduced to pure lead sponge.

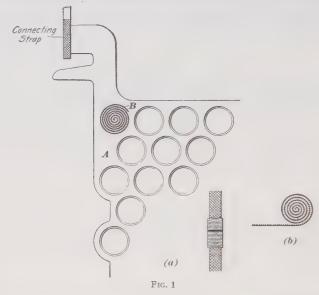
- 8. The Faure plate, invented at practically the same time by Faure in France and by Brush in the United States, consists of a grid provided with ribs, openings, or pockets, to which is applied the active material in the form of a paste consisting of red lead for the positive plate and of litharge for the negative. After the paste has set, the red lead of the positives is changed to lead peroxide and the litharge of the negatives to pure lead sponge by passing current through them in the proper direction in the forming bath of dilute sulphuric acid.
- 9. Relative Merits of Planté and Faure Plates.—The Planté plate is heavier, bulkier, and more costly than the Faure plate of the same capacity. The positive Planté plate is more durable than the ordinary Faure positive, but the durability of the two types of negatives is more nearly the same, especially if the same weight of material is used in each. The pasted positive is therefore used in portable cells, where minimum weight and space are of more importance than durability, and in cells for standby or emergency service, where but few charges and discharges are required per annum; the formed positive is used in stationary batteries in service requiring a comparatively large amount of work per annum, making durability of more importance. The negative Planté plate is standard with some manufacturers for stationary and car-lighting cells; it has the disadvantage that its capacity diminishes with use, owing to the tendency of the pure lead sponge to contract, harden, and lose its porosity. This tendency is counteracted in the Faure plate by the admixture of certain inert materials. Processes called permanizing have also been developed and patented for maintaining the capacity of the Planté negative. One such process consists in dipping the finished plate into a strong solution of sugar, and then carbonizing the sugar in the pores of the plate.

COMMERCIAL TYPES OF LEAD PLATES

10. The Manchester positive plate, details of which are shown in Fig. 1 (a), consists of a cast grid A of lead-antimony alloy perforated by circular openings, into which

rosettes, or buttons, B are forced by hydraulic pressure. Each button is formed by coiling into a spiral a strip of pure lead corrugated crosswise on one side, as shown in (b). When the buttons are in place, the corrugations are transverse to the plate and form the surfaces upon which the active material, lead peroxide, is formed by the accelerated Planté process.

The antimony in the grid renders it harder, stronger, and more rigid than one of pure lead, and also prevents electrolytic



corrosion, or formation, so that the grid remains intact throughout the life of the plate.

11. The Tudor positive plate, Fig. 2, consists of a pure cast-lead grid with both horizontal and vertical ribs, the openings between which extend entirely through the plate. The active material, lead peroxide, is formed in these openings on the transverse surfaces of the ribs by the accelerated Planté process. It is claimed that the absence of a central web, by permitting through-and-through circulation of electrolyte and, especially, by rendering the entire active material accessible

from either side of the plate, prevents the effect of unequal work on the two sides and makes the plate less subject to

buckling, or distortion, than the soft-lead plates having central webs.

12. The box negative, Fig. 3, has a grid of vertical and horizontal ribs of antimony-lead alloy forming pockets about 1 inch square. The active material, lead sponge, is retained in these pockets by perforated lead sheets. The grid is of the split type, originally cast in halves, the perforated sheet

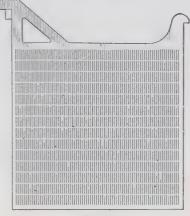
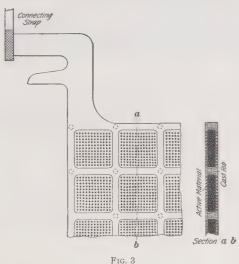


Fig. 2

lead being placed in the mold before casting. After the active material is placed in the pockets, the two parts are riveted



together and also leadburned (process described later) together at the lugs. The box negative is used with the Manchester or Tudor positive in all but the smaller sizes of cells.

13. The shelf negative, Fig. 4, is a pasted plate with a grid having main vertical ribs connected by short horizontal ribs, or shelves, be-

tween which is applied the active material. This type of negative is used in cells having plates 6 inches square or smaller.

14. The Gould positive plate, Fig. 5, has a pure lead grid made from a rolled-lead slab, or blank, upon the surface

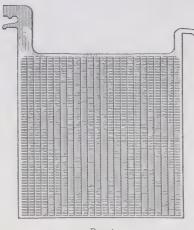


Fig. 4

of which are developed closely spaced vertical leaves, or fins, by a spinning process. The process consists in passing the blank back and forth between two shafts bearing a series of steel disks spaced by intermediate washers of smaller diameter. The disks are forced into the blank while the shafts are rotated at high speed, the lead being thus spun, or forced, into the spaces between the hard-steel disks

to form the leaves of the plate. The active lead peroxide is formed by the Planté process upon the surfaces of the leaves.

The plate has a central web, and is also stiffened by horizontal and vertical ribs where the blank has not been reached by the rotating disks. A vertical section of part of a plate is shown in Fig. 6.

The Gould negative plate is made in the same way as the positive, the peroxide being then reduced electrolytically to lead sponge.

15. The Willard positive plate, Fig. 7,

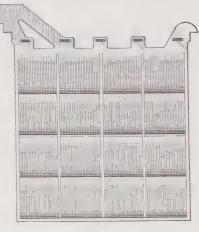
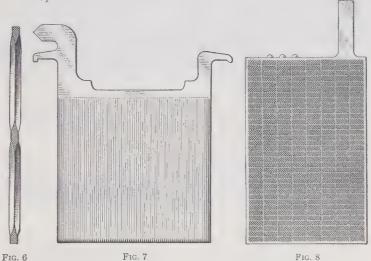


Fig. 5

has a pure lead grid made from a solid rolled-lead blank, upon the surface of which leaves are developed by a cutting tool, or plow, that cuts each leaf at an angle with the surface and turns it up without removing any of the metal. The leaves are tapered in section, being thicker at the base, and extend vertically from the top of the plate to the bottom, no ribs of undeveloped surface being left by the tool. The central web is heavier at the top of the plate than at the bottom. The active peroxide is formed on the surfaces of the leaves by the Planté process.

The Willard negative plate is practically the same in structure as the positive.



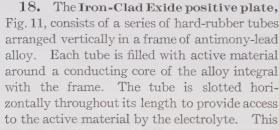
16. The Exide plates, positive and negative, are of the Faure type. As shown in Fig. 8, the grid consists of a series of vertical ribs connected by horizontal bars. The latter have a thickness less than that of the plate and are staggered as in Fig. 9, which shows a transverse vertical section of part of a plate. This design gives a large proportion of active material relative to the weight of the grid, tending to raise the output per unit weight of plate. This type of plate is recommended by the manufacturers for electric vehicles and for emergency reserve in connection with central lighting stations.

I L T 384-17

17. The Diamond grid, Fig. 10, has diagonal ribs staggered on opposite sides and connected by vertical ribs. The

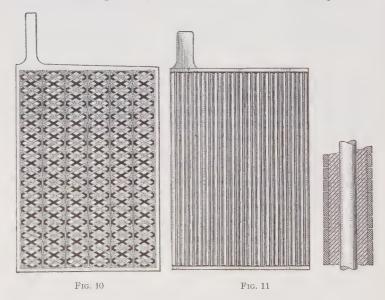
active material is pasted into this framework.

This type of plate is claimed to be very rugged and free from buckling, and is used principally for electric vehicles.



method of confining the active material in permanent contact with the core makes a very durable plate.

The Exide negative plate is used with Iron-Clad positive.

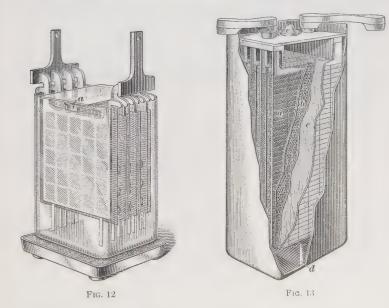


19. Plate Thickness.—Pasted plates for electric vehicles and similar service are made in various thicknesses, depending

on the conditions of service for which they are to be used. Within certain limits, a given weight of lead if made into many thin plates will give more capacity than if made into a few thick plates. The thin plates are more expensive per pound to manufacture, and, if used to their full capacity on each discharge, they have a shorter life per pound of lead than the thick plates. It is claimed that by using regularly only a part of the full capacity, the thin plate will give a greater life, in ampere-hours, than the thicker plate. Different manufacturers are not wholly agreed as to the most economical thickness of plate to use for given conditions.

COMPONENT PARTS OF THE LEAD CELL

20. The component parts of the lead cell are the element, comprising the positive-plate group and the negative group.



including connecting straps, or bus-bars, and the separators; the plate supports (in lead-lined tanks); the separator hold-

downs; the container, consisting of a glass or a rubber jar or a lead-lined wooden tank; the electrolyte; the cover; and the insulating cell support.

Three types of lead cells are shown in Figs. 12, 13, and 14, the first with a glass container, the second with a rubber-jar container, and the third with a lead-lined wooden-tank container. In Fig. 13 part of the cell is shown cut away in order to display the arrangement of the interior.

21. Grouping.—In order to obtain the desired amperehour capacity, the necessary number of plates, positive and

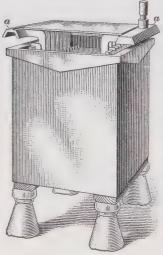


Fig. 14

negative, are grouped in each cell, all the positive plates being connected to one terminal and the negatives to the opposite terminal. Except in the two-plate, or couple, type of cell (described later), the outside plates of an element are always negative, making one more negative plate than positive; all the positive plates are thus worked as nearly equal as possible from both sides, equalizing expansions and contractions of the active material and minimizing the tendency to buckle. The negative plate is not subject to this tendency.

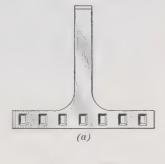
In assembling the plates into positive and negative groups for

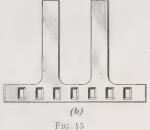
stationary cells, two types of cell terminal and intercell connection, \mathbf{T} straps and bus-bars, are standard. For cells of the smaller capacities in glass jars, up to and including fifteen plates $10\frac{1}{2}$ in. $\times 10\frac{1}{2}$ in., the \mathbf{T} strap, Fig. 15 (a), is employed. The lugs on the plates are inserted into the rectangular openings and secured by lead burning. Two straps are shown in place in Fig. 12. Connections between adjacent cells are made by bolting the vertical connecting straps together with brass bolts provided with lead-covered nuts. When, as

for very high rate discharge, low connection resistance is important, the connecting straps may be lead-burned together instead of using the bolt connectors or in addition to them. For cells containing nine or more plates $10\frac{1}{2}$ in. \times $10\frac{1}{2}$ in., the double **T**, Fig. 15 (b), is commonly used. When either kind of **T** strap is used, plates are assembled into groups at the factory.

Plates in lead-lined tanks, as well as $10\frac{1}{2}'' \times 10\frac{1}{2}''$ plates in extra-heavy glass jars, are assembled by lead-burning the

positive-plate lugs of one cell and the negative-plate lugs of the adjacent cell to a common bus-bar a. Fig. 14, between the cells. At points in the battery where current is to be taken from the series of cells, as at the ends of rows or between adjacent regulating, or end, cells (cells arranged to be cut into or out of circuit, as described later), the busbars are reinforced by embedding a copper bar in the lead, as shown in Fig. 16 (a) for cells of small capacity and in (b) for cells of large capacity. The copper reinforcement improves the conductance and insures uniform distribution to all the plates in the cell. Where bus-bars are used, plates are shipped separately and

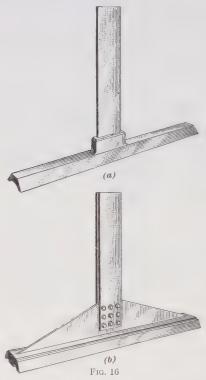




are lead-burned to bus-bars when the cells are set up. In cells of small capacity, only two plates, one positive and one negative, are sometimes used. These are called two-plate, or couple-type, cells. The positive plate of one cell and the negative plate of the adjacent cell are permanently lead-burned to a **U**-shaped connecting strap that supports the plates from the edges of the jars, as shown in Fig. 17, which illustrates a ten-cell battery.

A type of connector for electric vehicle cells is shown in Fig. 13.

22. Separators.—The use of vertical glass tubes for separating adjacent plates in stationary storage cells is practically obsolete; diaphragm separators of thin wood, Fig. 18, are now used in all stationary cells and in nearly all portable cells. In stationary cells, these diaphragms are supported in the slots of vertical dowels, which also serve to space the plates. In some cases, the dowels extend to the bottom



of the cell, as in Figs. 12 and 18 (a); in other cases, they extend to only the bottom of the plate, as in Fig. 18 (b). In the latter case, the middle dowel-or each dowel if only two are used—hangs on a hardrubber pin that passes through the dowel and rests on the tops of adjacent plates. The latter construction is preferable, as it leaves the space beneath the plates free for the removal of sediment. In stationary cells, wooden separators are prevented from floating by blocks of glass a, Fig. 12, called separator hold-downs. resting on the tops of the plates.

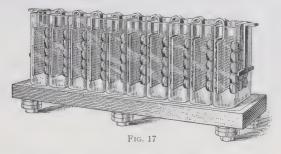
In portable cells, vehicle cells, automobile ignition

cells, and in large central-station batteries for emergency service, where plate spacing is reduced to minimize space and weight, the dowels are omitted and the wooden separators are grooved on one or both sides to provide for circulation of the electrolyte. In nearly all such cases, except central-station standby batteries, perforated sheets of hard rubber are inserted between the wooden separators and the adjacent positive plates, as

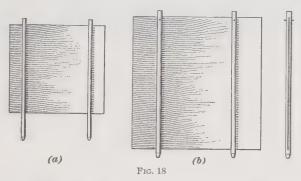
shown in Fig. 13, in which a is a positive plate; b, a rubber separator; and c, a wooden separator.

Wooden separators require a preliminary treatment for removal of organic acids, and must be kept constantly wet until installed in the cells.

Where the cells are subjected to considerable motion, as in train lighting and yacht lighting, but the plates are not



close enough together to hold the separators firmly in position, sheet-rubber separators are used alone. In cells for automobile ignition, starting, and lighting systems, wooden sepa-



rators are sometimes used alone, reducing the cost of the cells at a sacrifice of durability.

23. Plate Supports.—In all rubber jars, the plates rest on ribs d, Fig. 13, on the bottom of the jar. In lead-lined tanks for train lighting, the plates are set on porcelain rests of inverted V section on the bottom of the tank. In all

stationary cells with glass jars or wooden tanks, the plates are provided, on each side near the top, with lugs that rest on the edges of the glass jars, as in Fig. 12, or on vertical sheets of glass in lead-lined tanks.

24. Electrolyte.—The specific gravity of electrolyte for commercial cells varies from 1.200 to 1.300. The lower density is used in stationary cells, where there is space for an ample supply of electrolyte. The higher densities are used in portable cells, where the volume of electrolyte is restricted, in order to furnish a sufficient quantity of acid to combine with the active material of the plates and still maintain satisfactory density at the end of discharge.

Electrolyte must be free from certain impurities, such as chlorides, nitrates, iron, copper, arsenic, platinum. Some impurities, such as lead and calcium, are not injurious.

In referring to the density of electrolyte, the decimal point is sometimes omitted; electrolyte of 1.200 specific gravity, for instance, is called 1200 acid.

- 25. Covers.—Glass covers are generally used on stationary cells with lead-lined tanks or glass jars, as shown in Figs. 12 and 14. They serve to reduce the evaporation from the cells, and the spray that arises from the electrolyte toward the end of a charge condenses on the under surface of the cover and drops back into the cell. Cells in rubber jars, Fig. 13, are furnished with hard-rubber covers, usually sealed around the edges and around the projecting terminals with a compound of asphalt composition designed to remain plastic at low temperatures without becoming too soft when warm. The rubber cover is usually provided with a hole for filling that can be plugged with a soft-rubber stopper e, Fig. 13, having a small vent hole in the center.
- 26. Insulating Supports.—Cells in glass jars are supported on shallow trays of wood or glass filled with sand to distribute the weight of the cell uniformly over the bottom of the jar. Glass trays are preferable on account of durability, and can be obtained for all but the very largest sizes of cells.

Glass trays, Fig. 12, have glass feet; wooden trays, Fig. 17, rest on glass insulators of the petticoat type.

The most satisfactory support for cells with lead-lined tanks is the *oil insulator*, Fig. 19. The glass body a, in the shape of an annular trough, is half filled with oil and then covered

with a lead cap b. The upper outer edge of the glass trough is provided with a projecting lip and the lower edge of the lead cap is beaded internally to prevent water or acid from splashing into the trough. The glass trough rests on an earthenware



Fig. 19

pedestal c. Four of these insulators support the cell shown in Fig. 14.

Porcelain insulators, even though thoroughly glazed, have been found unsatisfactory for supporting lead-lined tanks, as the glazing eventually breaks down. Glass insulators in double tier, which superseded porcelain, would in many cases become coated with a film of acid and dirt, providing a path for leakage current that would in time puncture the lead lining of the tank by electrolytic action.

CHARACTERISTICS OF THE LEAD CELL

CAPACITY

27. The capacity of a storage cell, expressed in amperehours, is the product of the rate of discharge in amperes by the number of hours the cell will maintain that rate on full charge. The ampere-hour capacity varies with the rate of discharge, being less at high rates than at low rates. The capacity of a standard stationary cell is based on the *normal*, or 8-hour, rate of discharge. Trade catalogs give the 5-hour rate as 1.4 times the normal, the 3-hour rate as twice normal, and the 1-hour rate as four times normal. On this basis, the capacity of a cell at the 1-hour rate is just one-half its capacity at the 8-hour rate. On test, a cell that will give 8 hours at normal rate will usually give somewhat more than 1 hour at four times normal; and a cell that will give just 1 hour at the catalog 1-hour rate will give only about 7 hours at normal rate. However, if a cell having the full 8-hour capacity at normal rate of discharge is worked regularly at the 1-hour

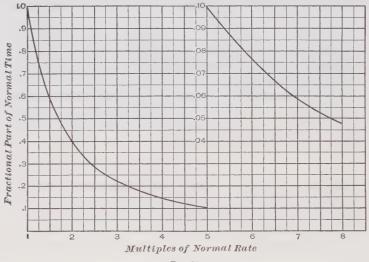


Fig. 20

rate, its capacity will fall off until it settles down to 1 hour at the 1-hour rate. Conversely, a cell with a capacity of just 1 hour at the 1-hour rate and 7 hours at normal rate, if worked regularly at the latter rate will increase in capacity eventually to about 8 hours, instead of 7, at the normal rate. The ratings in trade catalogs are based on these facts.

Capacities of vehicle cells are usually stated at the 4-, $4\frac{1}{2}$ -, or 5-hour rate. The capacities of batteries for gasoline-engine ignition are usually given in ampere-hours at the service rate, which is generally based on the 20-hour rate of discharge.

28. In Fig. 20 is a curve that shows the relation between discharge rate and time for a standard stationary cell. The rates are given in multiples of normal rate, and the corresponding times in fractional parts of the normal time. The curve is drawn in two parts, to different scales, in order to make the small values of fractional parts of time more readable.

The relations shown by the curve apply to continuous and constant rates of discharge only. If the discharge is intermittent, the available capacity will be increased to an extent depending on the total elapsed time over which the intermittent discharges are distributed. Thus, if brief discharges at the 1-hour rate are distributed with approximate uniformity over a period of 8 hours, nearly full 8-hour capacity will be obtained.

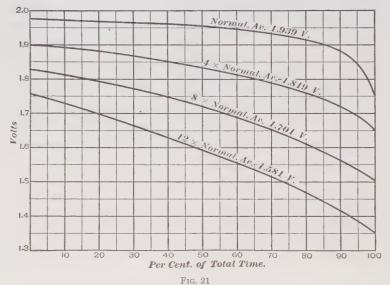
VOLTAGE

- 29. The total electromotive force, in volts, that is generated within a storage cell by the chemical action and that is effective in producing current through the total resistance of the entire circuit, including the internal resistance of the cell, is the internal, or true, voltage of the cell. The external voltage of a cell is that which can be measured by connecting a voltmeter across the cell terminals; it is equal to the internal voltage minus the drop through the internal resistance. If the cell is delivering no current, the internal and external voltages are equal.
- 30. The open-circuit voltage of the lead storage cell is from 2.05 to 2.08; and if a cell is allowed to remain on open circuit a sufficient length of time, its external voltage will settle to something between these values, whether the cell is fully charged or practically discharged. The open-circuit voltage of a cell is, therefore, no guide to the state of charge.

The so-called floating voltage of a cell is the voltage that must be maintained across its terminals to keep it in a constant state, neither charging nor discharging. The value of the floating voltage, from 2.08 to 2.1, must be slightly higher than the open-circuit voltage in order to compensate for

local action, or so-called self-discharge, which is due to electrochemical action in small circuits within the plates themselves.

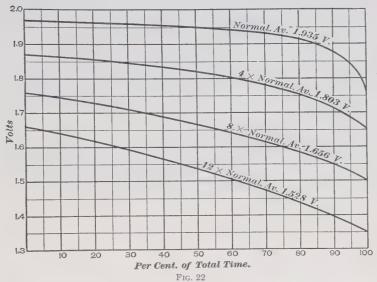
31. Discharging Voltage.—During discharge the external voltage of a cell drops below the open-circuit voltage by an amount that varies with the rate and duration of the discharge. This drop in voltage is due to two causes. The drop that takes place instantly on starting the discharge is due to the internal resistance of the cell and is directly proportional to the current; the additional drop, which occurs



slowly at first and then more rapidly as the discharge proceeds, is due to so-called *polarization*, which is caused largely, if not wholly, by the weakening of the acid in the pores of the plates. The final voltage at the end of discharge at the normal rate is 1.75; at the 1-hour rate, 1.6 to 1.65—voltage readings to be taken while the cell is still delivering current. Fig. 21 shows discharge voltages at several different rates for cells with plates $10\frac{1}{2}$ in. \times 11 in., Tudor positive and box negative, and Fig. 22, for cells with plates $15\frac{5}{6}$ inches square, Tudor

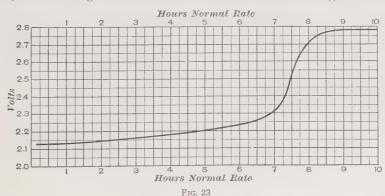
positive and box negative. The rate of discharge, in terms

of a multiple of normal, and the average voltage for the discharge are given beside each curve. The instantaneous drop



at the beginning of discharge is not shown in Figs. 21 and 22.

32. Charging Voltage.—When charging current, is passed through a cell, the instantaneous rise of voltage above



the open-circuit value is due to internal resistance, and the subsequent gradual rise is due to polarization caused by the

strengthening of the acid in the pores of the plates. Toward the end of a complete charge, a further rapid rise in voltage occurs, due to the collection of bubbles of oxygen and hydrogen in the pores of the positive and negative plates, respectively—the result of the decomposition of the electrolyte, which occurs when practically all the active material in the plates has been brought to the state of full charge. The final voltage at the end of a charge at normal rate, with the charging current still flowing, is from 2.6 to 2.8. This applies to comparatively new cells; those which have been in service for several years may not exceed 2.5 or 2.4 volts at the end of charge. In Fig. 23 is shown a curve of charging voltage at normal rate. It will be noted that the voltage does not rise appreciably after the end of the regular charge at $8\frac{1}{2}$ hours.

INTERNAL RESISTANCE

33. The internal resistance of a cell or a series of cells is best measured after discharging at constant rate long enough to obtain a steady voltage at the terminals, and then quickly interrupting the discharge and noting the instantaneous rise of voltage. This instantaneous rise divided by the value of the current at the instant of interruption gives the true internal resistance. Instead of completely interrupting the discharge, the current may be suddenly reduced or increased by a definite amount, and the internal resistance found by dividing the instantaneous change in voltage by the change in current. The internal resistance of standard stationary cells is such as to cause an instantaneous drop in voltage of 6 to 7 per cent. when subject to a momentary discharge equal to the 1-hour rate.

The polarization drop, which occurs within a few seconds after the discharge begins, may add from 20 to 30 per cent. to the internal resistance drop, and in many calculations may be treated as a true ohmic drop.

SPECIFIC GRAVITY OF ELECTROLYTE

34. As previously stated, the specific gravity of the electrolyte of a lead cell decreases during discharge, the initial specific gravity being restored on charge. In stationary cells, the maximum specific gravity is about 1.210, which drops to 1.170 or 1.180 at the end of a complete discharge. The range of specific gravity varies with the total amount of electrolyte in the cell as compared with the capacity of the plates. When this range is once determined, the state of charge of a cell can be ascertained at any time by observing the specific gravity, which varies in direct proportion to the ampere-hour capacity remaining in the cell.

In vehicle cells, the maximum specific gravity is about 1.275, and in automobile ignition cells, 1.300, with a minimum at the end of discharge of about 1.100 in both types.

TEMPERATURE

35. The foregoing data on lead cells are based on a cell temperature of 70° F.

The capacity of a lead cell decreases with reduction of temperature. At normal rate, the loss amounts to about six-tenths of 1 per cent. of the 70° capacity for each degree reduction in temperature. At higher rates, the percentage of loss is somewhat greater.

The internal resistance of a lead cell increases with reduction in temperature. At 0° F, the internal resistance is about double that at 70° F.

The specific gravity of the electrolyte varies also with temperature in the proportion of an increase of 1 point (.001) in specific gravity for every drop in temperature of 3 degrees (F). This correction must be applied and the observed specific gravity reduced to the equivalent at 70° F. before using it as a guide to the state of charge of the cell.

EFFICIENCY

36. The ampere-hour efficiency of a storage cell is the ratio of the discharge, in ampere-hours, to the charge, in ampere-hours, required to bring the cell back to the same state of charge. The ampere-hour efficiency can be reduced to almost any low value by excessive and unnecessary over-charge. Aside from this, the legitimate ampere-hour efficiency

varies with a number of conditions: the age and condition of the plates, the temperature, the rate of charge, the elapsed time between charge and discharge, the ratio of the amount of discharge to the battery capacity, and the particular states of charge and discharge between which the battery is worked. Under average conditions, an ampere-hour efficiency of 90 per cent. can usually be obtained.

The ampere-hour losses are due to two causes: local action, or so-called self-discharge, and gassing during charge. Local action may be caused by impurities in the plates or electrolyte or by local short-circuits, and the effect of these is increased at high temperature and by long standing; but under normal conditions this cause of low efficiency is almost negligible. Gassing is the term applied to the evolution of hydrogen and oxygen gases, due to the decomposition of the electrolyte when a charge has been continued to a point where very nearly all the active materials have been converted either into lead peroxide or metallic lead. The effect of gassing can be reduced by reducing the charging rate as

Fig. 24 can be reduced by reducing the charging rate as soon as gassing appears. Under ideal conditions, an amperehour efficiency of almost 100 per cent. may be realized.

37. The watt-hour efficiency of a storage cell is the ratio of the energy taken out of the battery to that put in, both measured in watt-hours. It is equal to the ampere-hour efficiency multiplied by the voltage efficiency, that is, by the

ratio of average voltage during discharge to average voltage during charge. The watt-hour efficiency, therefore, depends not only on the factors that affect the ampere-hour efficiency, but also on those which affect the voltages of charge and discharge. The voltage efficiency depends principally on the rate of charge and discharge, as well as on the size and type of plates, the cell temperature, and the range through which the battery is worked. The average voltage and resulting voltage efficiency can be obtained from the charge and discharge curves. Under test conditions, a watt-hour efficiency of 85 per cent. may be obtained with charge and discharge at normal rate, and even higher if the charging rate is tapered, or lowered toward the end, to avoid gassing and high final voltage.

Efficiency tests should include several cycles of charge and discharge, in order to reduce the effect of error in determining when the original state of charge has been restored.

CARE AND OPERATION OF LEAD BATTERIES

TESTING INSTRUMENTS AND APPARATUS

38. The hydrometer, one style of which is shown in Fig. 24, is used for measuring specific gravities of electrolytes; this instrument can be obtained with numbered scales ranging between 1,100 and 1,300. One or more hydrometers of the type illustrated can be kept floating in the electrolyte of a stationary battery. In vehicle and other portable cells, however, there is not enough space for inserting a hydrometer, and part of the electrolyte must be withdrawn with a syringe and removed to a test-tube or some vessel in which the hydrometer can be floated. A more convenient device is the hydrometer syringe, Fig. 25, consisting of a rubber bulb provided with a glass barrel containing the hydrometer. The electrolyte is drawn up into the barrel until the hydrometer floats, when the reading may be taken and the electrolyte returned to the cell.

In order to correct specific-gravity readings for variations of temperature, as well as to guard against excessive temperature in portable and vehicle cells during charge, a thermometer must be provided. Floating thermometers can be used in stationary cells.

In order to follow the operation of a large stationary battery intelligently, it is customary to select one cell as a pilot cell,

the condition of which serves as a guide to that

of the entire battery.

- 39. In stationary batteries of considerable magnitude, such as are installed in connection with central power stations, compensating and recording hydrometers are usually employed. The compensating hydrometer is provided with an internal chamber filled with electrolyte and communicating with the external electrolyte in a pilot cell through a small outlet so curved as to provide a liquid seal. The expansion and contraction of the electrolyte in the chamber compensates for changes of temperature. This hydrometer is suspended from the arm of the recording device, which arm carries a pen that records the changes of specific gravity on a record sheet moved by clockwork. This instrument is provided with contacts for closing a circuit and giving a signal when the specific gravity reaches a certain maximum or minimum.
- **40.** The record of a compensating hydrometer is a reliable indication of the state of charge of a battery only when the water lost from the pilot cell by evaporation and gassing is constantly re-

placed to the same level. This is accomplished by means of the automatic pilot-cell filler, Fig. 26, which consists of a bottle of pure water provided with a curved-tube outlet having a small hole at the lowest point of the tube, normally below the surface of the electrolyte. When the level of the electrolyte falls, a bubble of air passes through the tube into the bottle, thus releasing an equivalent volume of water.



41. A low-reading voltmeter is also an important instrument for reading the voltage of individual cells. The scale should have a range from 0 to 3 volts, divided into tenths. A double-scale voltmeter is still more convenient, the lower scale having a range of three volts, and the higher scale having a sufficient range to read the maximum voltage of the entire series of cells.

42. An ampere-hour meter is a very convenient instrument for indicating the state of charge of a battery and deter-

mining the proper amount of charge to be given. These instruments can be obtained with a dial scale and a pointer adjusted to make one revolution for a complete discharge and return toward the zero position during charge. If the pointer travels at the same rate for charge and discharge, it can be set ahead by 10 or 15 per cent. just before the charge begins, so that when it has returned

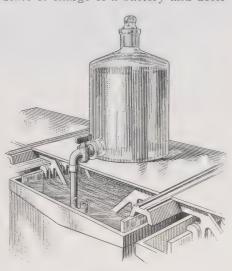


Fig. 26

to zero the desired amount of overcharge will have been given; or the instrument can in some cases be so adjusted that the pointer travels 10 or 15 per cent. slow during charge, requiring an excess charge of 10 or 15 per cent., in ampere-hours, to bring it back to zero. These ampere-hour meters are sometimes provided with a contact that trips a circuit-breaker in the charging circuit when the pointer has returned to zero, thus stopping the charge automatically. Such instruments are satisfactory where the rates of charge and discharge do not vary over too wide a range; they are reasonably accurate from 50 per cent.

of overload down to 5 per cent. of rated capacity; but if any considerable proportion of the charge or discharge takes place at rates outside of the range of accuracy, the indications will be misleading.

OPERATION AND CARE

43. Assembling.—Special instructions are furnished by the manufacturers for assembling and connecting up the cells of a battery. The following are the more important precautions to be observed:

The positive and negative groups should first be assembled in the containers and connected up *before* the electrolyte is put in, the positive terminal of each cell being connected to the negative terminal of the adjacent cell. The wooden separators should be kept wet until they are placed in position in the cells, and the electrolyte should then be added before the separators are allowed to dry.

Electrolyte of the proper density for immediate use is usually furnished. If strong acid (oil of vitriol, or 1.800 specific-gravity acid) is obtained, it must be diluted with pure water before being poured into the cells. This diluting, or "breaking down," of strong acid must be done with great care, as a large amount of heat is developed during the operation. Never add the water to the acid, as this will produce dangerous sputtering. Add the acid to the water very slowly, especially when a glass vessel is used, to avoid cracking the glass with excessive heat, and stir constantly during the process. Allow the mixture to cool before putting it into the cells.

44. Polarity.—Before connecting a battery to the charging circuit, the polarity (positive or negative) of each of the two conductors of the charging circuit must be determined. If there is any doubt as to this, a simple test may be made by connecting two wires, one to each conductor of the supply circuit, with enough resistance in series to limit the current to about 1 ampere or less, and then dipping the two wires in a vessel of acidulated water or in water in which a small amount of common salt has been dissolved, keeping the ends

of the wires about an inch apart. The wire from which bubbles of gas are given off more freely is connected to the negative side of the circuit. The positive terminal of the battery must then be connected to the positive conductor of the circuit, and the negative terminal to the negative conductor. The positive terminal of a stationary battery may be distinguished by the dark-brown color of the plates to which it is connected, the negative terminal being connected to the slate-gray plates. The terminals of portable batteries, in which the cells are sealed, preventing inspection of the plates, are usually marked for polarity. If they are not marked, a voltmeter may be used or the test just described may be employed.

- 45. Initial Charge.—Immediately after assembling and as soon as possible after the electrolyte has been put into the cells, charging should be started and continued at the 8-hour rate, with as little interruption as possible, for a period of from 35 to 60 hours, depending on the type of plate. Special instructions are furnished by the manufacturers.
- 46. Regular Charge.—A regular charge is given to the battery as frequently as may be necessary to restore the energy taken out on discharge. This regular charge can be given at the normal rate throughout; but if it is necessary to hasten the charge, a considerably higher rate can be used at the beginning, provided the rate is reduced from time to time to prevent violent gassing and to keep the temperature of the cells below 110° F. The regular charge should be continued until the specific gravity of the pilot cell is from 3 to 5 points below the maximum reached on the preceding overcharge. All the cells should then be gassing moderately, but not so freely as at the end of overcharge.

When a battery has been completely discharged, the charge should be started as promptly as possible. Long standing in a discharged condition tends to produce in the plates a hard and crystalline form of lead sulphate that will reduce their capacity temporarily. This sulphate may not cause permanent injury, because it can be decomposed by a long overcharge at low rate.

- 47. Periodic Overcharge.—Once every week or two a battery should receive an overcharge, which consists in prolonging the regular charge at normal rate until the specific gravity of the pilot cell has reached a maximum and remains stationary for 1 hour, and all the cells are gassing freely. The object of this overcharge is to bring all the cells to a uniform, healthy condition.
- 48. Indication of a Complete Charge.—The most reliable indication of a complete charge in a lead cell is the fact that the voltage and the specific gravity have reached a maximum and become stationary for 15 minutes to $\frac{1}{2}$ hour, the charging current being maintained constant. These final values of voltage and specific gravity are not always the same, the former varying with the temperature, the rate of charge, the type of plates, and the age of the battery, and the latter with the temperature, the height of electrolyte, and the amount of acid lost by spraying or combination with sediment in the bottom of the cells. The theoretical values of voltage and the specific gravity are not therefore a sure indication of complete charge.

An ampere-hour meter connected into the battery circuit, both during charge and discharge, is usually a very satisfactory guide in determining the proper amount of charge. In general, an excess of from 10 to 15 per cent. in charge over discharge, measured in ampere-hours, is desirable to keep the cells in good condition. (See Art. 42.)

Toward the end of the charge the cells will gas very freely, an indication, in a healthy cell, that the charge is approaching completion. Plates that are badly sulphated (see Art. 46) will gas freely long before the charge should be stopped.

While charging vehicle or other portable cells in sealed rubber jars, the soft-rubber stoppers in the covers should be removed and the cover of the battery box or compartment should be left open.

It should always be carefully borne in mind that the gases, oxygen and hydrogen, given off by a battery toward the end of charge form an explosive mixture. The battery room or

compartment should therefore be freely ventilated at such times, and the proximity of an exposed flame should be absolutely prevented.

- 49. Effect and Remedy of Short Circuit.—At the end of the charge preceding the overcharge, the specific gravity of the electrolyte in each cell should be read and recorded. If the specific gravity of any cell is markedly lower than that of the others, that cell should be examined for short circuits. Such a cell should be carefully inspected during the overcharge to note whether it gasses later or less freely than the others. If the short circuit has been removed, the overcharge will probably bring the cell back to normal condition. If the cell is very low as compared to the others, full capacity may not be completely restored until after the second overcharge. Sometimes the cell must be cut out of circuit and treated to a prolonged charge at normal rate separately
- 50. Discharging.—The only limit to the rate of discharge of a lead cell is the safe carrying capacity of the plate lugs and connections. Four or five times the 1-hour rate may be taken from a cell for a few minutes, and even higher rates momentarily if special high-capacity plate lugs are furnished. Excessive discharge, in ampere-hours, at low rate should be avoided as far as possible, and if such discharge should occur the cells should be recharged as soon as possible.
- 51. Filling Cells.—The electrolyte should be kept above the tops of the plates by filling the cells with pure water from time to time. Under normal conditions of temperature and ventilation, filling once a week is usually sufficient. Acid should never be added to the cells except by special instructions from the manufacturer. The acid in the electrolyte does not evaporate. A very small amount of acid may be carried off in spray during charge, but the greater part of this is retained by the covers, so that the loss from this cause is appreciable only after a year or two of service. A small amount of acid is also lost when sediment is removed from the cells.

In some cases, the local supply of water is sufficiently pure to use for filling the cells. Rainwater caught on a clean slate or a shingle roof is usually satisfactory, provided the atmosphere is not contaminated with soot or other foreign particles. The roof should be allowed to flush off for a while before the water is collected for use in the battery. Battery manufacturers will usually make, without charge, the necessary tests to determine the purity of local water supply. A quart sample of water should be furnished for such test.

If the local supply of water is not sufficiently pure, distilled water can usually be purchased. A still is often installed for purification of the water required by a large battery.

Water for filling cells should be stored and handled in wooden, earthenware, or glass vessels; iron or other metal should be avoided.

The amount of evaporation varies with the temperature, atmospheric humidity, and character of ventilation. Under average conditions, the height of the electrolyte in the cells may be reduced from $\frac{1}{2}$ to $\frac{3}{4}$ inch per week. This depth, together with the number and dimensions of the cells, will give the quantity of water required per week for filling.

Example.—The depth of electrolyte in a battery of 200 cells is reduced $\frac{1}{2}$ inch per week by evaporation. Each cell is $25\frac{1}{2}$ in. \times 12 in., inside dimensions. How many gallons of water per week will be required to replace the less by evaporation?

Solution.—The amount of water lost by evaporation is $200 \times .5 \times 25.5 \times 12 = 30,600$ cu. in. One United States gallon contains 231 cu. in.; therefore, $30,600 \div 231 = 132.5$ gal., nearly, will be required. Ans.

52. Battery-Room Ventilation.—The battery room, or compartment, should be well ventilated, especially during charge, to prevent excessive rise of temperature, to remove acid spray before it collects on tanks, insulators, etc., and to prevent the accumulation of explosive gas mixtures. In small installations, good natural ventilation by doors and windows is satisfactory. For large batteries, artificial ventilation is frequently employed, preferably by exhausting the air at one end of the room near the top, allowing the fresh air to enter at the other end near the floor through numerous openings of large aggregate area.

53. Removal of Sediment.—In service, a certain amount of the active material of the plates is dislodged and falls to the bottoms of the cells. This sediment must be removed before it accumulates in sufficient quantity to touch the bottoms of the plates and short-circuit them.

Sediment can be removed from small cells by removing the element (being careful to press the plates together to retain the separators in position), pouring off the clear electrolyte, flushing out the sediment, replacing the element, and pouring back the clear electrolyte. Loss of electrolyte can be made up by adding fresh electrolyte of the same density.

The work should be done on one cell at a time, and the element should remain exposed to the air no longer than absolutely necessary.

If the cells are too large to be handled in the manner just mentioned, the sediment can be removed with a scoop of wood or aluminum of special design, Fig. 27, having a horizontal blade of L section with a vertical handle at one end. The scoop is inserted between the outer negative plate and the side of the jar, with the vertical edge of the blade against the side of the jar and the horizontal edge on the bottom, the handle



Fig. 27

rising at one corner. By using the handle as an axis, the blade is swept over the bottom of the jar under the plates through an angle of 180°, the handle being at the same time moved along the side of the jar until it is brought to the opposite corner, still in a vertical position. The blade is thus again brought against the side of the jar in reversed position with its vertical edge away from the jar wall. By holding the blade against the side of the jar, the scoop can be raised, bringing the sediment with it. Wooden scoops are used with glass jars, because they are less liable to crack the jars. Either wooden or aluminum scoops can be used with lead-lined tanks.

- 54. Cutting Out Plates.—If it is necessary to remove individual plates from a cell, a full charge should first be given. The plates can be conveniently stored in the free spaces at the ends of near-by cells or in a separate jar or tank filled with electrolyte; but positive and negative plates should not be brought into contact with each other nor with the lead lining of the same tank. If more convenient, positive plates can be removed and allowed to dry in the air without washing or other special precaution. If it is necessary to permit negative plates to dry, they should first be thoroughly washed with pure water to remove all electrolyte. A fully charged negative plate, especially when comparatively new, if allowed to dry in the air, will oxidize so rapidly as to produce considerable heat. If this heat becomes excessive, the plates should be sprayed with cold water. Negative plates thus discharged in the air require a prolonged overcharge, similar to the initial charge, when again put in service, which operation subjects the positive to excessive overcharge; negatives should therefore be kept immersed in electrolyte, if possible.
- 55. Putting Battery Out of Commission.—If the use of the battery is to be entirely discontinued for a period not longer than 9 months and it is not practical to charge at least once a month, care should be taken that an overcharge is given just before the idle period. Water should be added to the cells during the overcharge so that the gassing will insure thorough mixing. The level of the electrolyte should be about $\frac{1}{4}$ inch from the top of the jars. After the overcharge is completed, the operator should make sure that all the cell covers are in place and should remove the battery fuses. Though not likely, the level of the electrolyte may, owing to excessive evaporation during the idle period, fall below the top of the plates; if this should occur, water must be added to keep them covered; if in a place where freezing is apt to occur, the electrolyte should be stirred after adding the water to insure thorough mixing.

If the battery is to be entirely out of service for more than 9 months, the procedure is as follows: After thoroughly

charging the cells, the electrolyte, which may be used again, is siphoned into thoroughly clean glass receptacles. As each cell is emptied, it is immediately filled with fresh, pure water, and when all the cells are filled, the battery is allowed to stand for 12 to 15 hours. The water is then siphoned out of each cell, after which the battery can be allowed to stand indefinitely. Any considerable sediment in the cells should be removed before it dries. If wooden separators are used, they are discarded, and replaced by new ones when the battery is put into service again.

56. Returning Battery to Commission.—If, in taking a battery out of service, the electrolyte has not been withdrawn, the battery can be returned to service by adding water, if needed, to the cells and overcharging the battery until the specific gravity of the electrolyte in the pilot cell has ceased to rise during a period of 5 hours.

If the battery has been standing without electrolyte, new wooden separators are installed and the cells then filled with electrolyte of 1.210 specific gravity. If the old electrolyte has been saved, only enough new electrolyte to replace any loss is added. The battery is then charged for 35 hours at the normal rate, or for a proportionately longer time at a lower rate. If the specific gravity of the electrolyte is low after the first charge, it should be restored to standard by the addition of acid.

57. Sulphation.—As stated in describing the reactions in the lead cell, Art. 4, sulphate of lead is formed in the active material of the plates during discharge. Under normal conditions, this sulphate is in a very finely divided state, and is readily decomposed by the electric current during charge. If the plates are allowed to remain in the electrolyte in a discharged condition for a considerable length of time, especially after an exhaustive discharge at low rate, a condition that may result, for example, from a short-circuit or a partial short-circuit in the cell, these normal and finely divided sulphate particles coalesce into larger masses, which are hard and crystalline and are much more difficult to decompose.

The remedy for this objectionable sulphation is a prolonged charge at not greater than half the normal rate. Higher rates do not hasten the process, but merely produce unnecessary heat and gassing.

58. Lead Burning.—In making joints between lead and lead, repairing tank linings, etc., solder cannot be used, because it is subject to attack and corrosion by acid. For such work, a process called lead burning is employed, requiring a blowpipe with a flame produced by the admixture of hydrogen and air under pressure. The supply of each is controlled by an independent stop-cock. The hydrogen is produced in a hydrogen generator by immersing scraps of zinc or iron in dilute sulphuric acid. Ordinary illuminating gas is sometimes used instead of hydrogen, but the hydrogen flame is hotter and more effective. Compressed air is usually obtained by forcing air into a receiver with a hand pump.

In lead burning, no flux of any kind is used, but the surfaces to be joined are partly fused with the blowpipe and the space between is filled by melting down a strip of lead drop by drop. Special forms, such as burning tongs or iron blocks, are used to retain the molten metal in place while cooling. Seams and repairs for tank linings are made in a similar manner; but, on account of the thinness of the sheet lead, a much greater degree of skill is required than for burning plate lugs, connectors, etc., and work on tank linings should not be undertaken until considerable experience and skill has been acquired.

A lead-burning apparatus in which the electric arc furnishes the heat has also been developed. Current for the arc is obtained from two or more cells of the battery on which the work is being done.

NICKEL-IRON-ALKALINE CELL

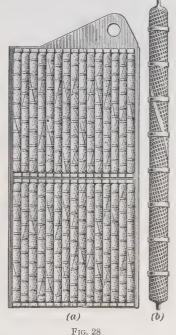
CONSTRUCTION

59. Plates.—The positive plate, Fig. 28 (a), of the nickeliron cell consists of a number of hollow tubes, or pencils, of perforated steel, nickel-plated, supported vertically in a nickel-

plated steel grid. The pencils, Fig. 28 (b), are made of steel ribbon wound spirally with overlapping riveted seams, and are reinforced at intervals by steel bands. The active material consists of nickel peroxide and flake nickel tamped into the tube in alternate layers, the flake nickel being added to increase the conductivity.

The negative plate, Fig. 29, consists of rectangular pockets of perforated nickel-plated steel supported in a nickel-plated steel grid, the pockets being filled with finely divided iron oxide, which is reduced to metallic iron by the initial charge.

60. Assembly.—As in the lead cell, the positive and nega-



lead cell, the positive and negative plates of the nickel-iron cell alternate, with negatives outside, there being one more negative than positive. The plates of each cell are assembled into positive and negative groups by bolting the corresponding lugs together and to the terminal

posts by means of steel connector rods with clamping nuts at each end, the plate lugs being spaced apart by steel washers. All steel parts are nickel-plated. Fig. 30 shows the plates of one cell assembled.

61. Separators and Electrolyte.—The plates are separated from each other by vertical strips of hard rubber, square in section, inserted with their vertical edges against the plates, as shown in Fig. 31, which is a view of a cell from above.

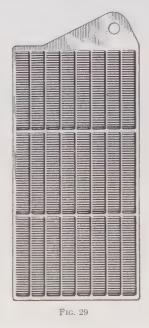


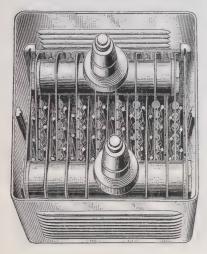


Fig. 3

Sheets of hard rubber are inserted between the outside negative plates and the jar, and hard rubber bridges a, Fig. 30, notched to receive the vertical edges of the plates, serve to separate these edges from the sides of the jar. The plates rest on hard-rubber bridges on the bottom of the jar, as shown in Fig. 30.

The electrolyte is a dilute (21 per cent.) solution of potassium hydrate (caustic potash), specific gravity approximately 1.200. A small amount of lithia (lithium hydroxide) is added.

62. Container.—The container of the nickel-iron cell is a box made of nickel-plated sheet steel, corrugated to give added stiffness, the cover being welded on after the element is in place. The two terminal posts a and b, Fig. 32, pass through circular openings provided with rubber bushings. Another opening in the cover, used for filling the cell, is closed by a spring cap containing a valve c that allows the gases



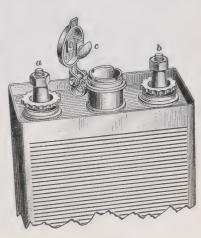


Fig. 31

Fig. 32

to escape during charge, but excludes the external air. In an earlier design, there were two openings in the cover, one for filling and the other for the vent valve.

CHARACTERISTICS OF THE NICKEL-IRON CELL

63. Capacity.—The rated capacity of the nickel-iron cell is based on a 5-hour discharge rate. The actual capacity in ampere-hours, however, is but little affected by variation of discharge rate, provided no limit is set to the final voltage In order to obtain maximum ampere-hour capacity at the higher rates, the final voltage must drop to a point too low for many classes of service.

Though the rated capacity is obtained by charging at the normal 5-hour rate for about 7 hours, it is possible, by giving the cells an excessive overcharge (16 hours at normal rate), to obtain on the subsequent discharge an increase in capacity of about 25 per cent. This excess is therefore obtained at a sacrifice in efficiency.

64. Voltage.—The open-circuit voltage of the nickel-iron cell is about 1.5 volts when fully charged. After a substantial discharge, the open-circuit voltage is restored only very slowly, and never completely until a freshening charge has been given.

In Fig. 33 are curves that show charge and discharge voltages of the nickel-iron cell at normal rate. The discharge curve,

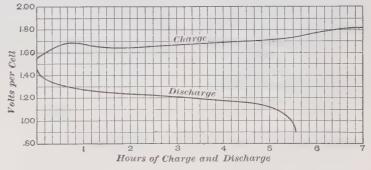


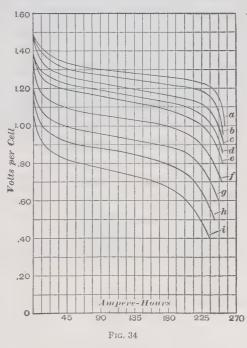
Fig. 33

as shown, is carried to .9 volt, though the normal-rate discharge is seldom carried below 1 volt in practice. The manufacturers recommend providing a charging voltage of 1.85 per cell. In Fig. 34 are shown discharge curves of the Edison cell at the various rates given in Table I. The cell temperatures for these curves are probably high because heat is developed in the cell during charge and discharge.

In Fig. 35 are curves that show the initial, average, and final voltages of the Edison cell at various discharge rates as compared with similar characteristics of the lead cell. The comparison is made between 60 nickel-iron cells and 42 lead cells to obtain practically the same open-circuit voltage.

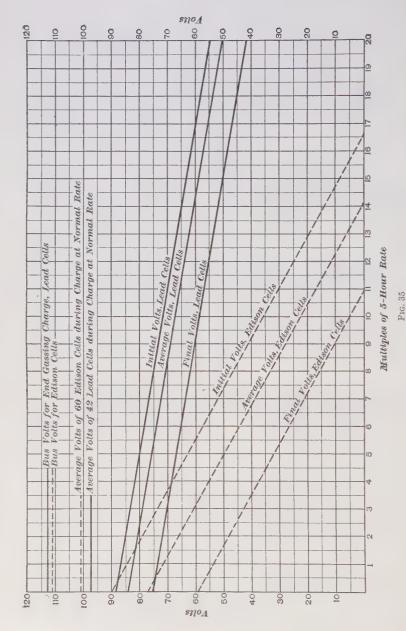
65. Temperature.—The effect of temperature on the capacity of the nickel-iron cell is peculiar. Starting from a cell temperature of 100° F. and reducing the temperature gradually, the capacity falls off slowly about 10 per cent. until the temperature is reduced to a certain critical point, beyond which a few degrees further reduction of temperature reduces

the capacity rapidly to about 10 per cent. of normal. The critical temperature at which this change takes place depends on the rate. At the 5-hour rate, it is about 40° F.: at twice the 5-hour rate, it is between 50° and 60° F. It should be noted that these are cell temperatures. Inasmuch as considerable heat is developed during both charge and discharge, the cell temperature is usually considerably higher than that of the outside air, especially if



the battery compartment is designed to retain the heat.

66. Resistance and Efficiency.—The internal resistance of the nickel-iron cell is such as to cause a drop of approximately 7 per cent. of the open-circuit voltage with an increase of current equal to the 5-hour rate. At ordinary operating temperatures, the internal resistance of a battery of Edison cells is approximately three times that of a lead cell of the same capacity and voltage, and this ratio is increased at lower temperatures.



The efficiency of the nickel-iron cell is lower than that of the lead cell under similar conditions. Not only is the difference in voltage between charge and discharge proportionately greater in the nickel-iron cell, but the ampere-hour efficiency is low on account of the gassing that occurs during the entire charging period. A watt-hour efficiency of 50 to 60 per cent. in commercial operation is about as high as can be expected,

TABLE I
DISCHARGE VOLTAGES, EDISON CELL

Curve	Rate of Discharge (Multiple of Normal)	Average Voltage	Hours of Discharge
а	1/3	1.272	17.040
b	$\frac{2}{3}$	1.240	8.475
С	I	1.203	5.690
d	$1\frac{1}{2}$	1.165	3.740
e	2	1.116	2.810
f	3	I.02I	1.852
g	4	.921	1.375
h	5	.836	1.083
i	6	.731	.875

and this figure may be reduced if an attempt is made to utilize the maximum capacity of the battery.

67. Advantages and Applications.—The principal advantages of the nickel-iron cell are durability, mechanical ruggedness, and ability to withstand neglect and abuse without injury. Life curves published by the manufacturers as a result of laboratory tests show a maximum of 1,100 complete discharges. The cell is not injured by standing in a discharged condition, nor by excessive overcharge, provided excessive temperature is avoided. At low rates of discharge, the nickel-iron cell is considerably lighter than the lead cell for the same watt-hour output; but this difference in weight disappears as the rate of discharge increases, on account of the pro-

portionately lower voltage of the nickel-iron cell. The Edison cell is, therefore, best adapted for service at low discharge rates where the cost of charging current is low, where light weight is important, and where but indifferent care and attention are given. On the other hand, the nickel-iron cell is not well adapted for high rates of discharge, nor for service in which the cost of charging current is high, nor where a battery must retain its charge for a long period of time without recharging.

OPERATION AND CARE

68. Charging.—The state of charge of the nickel-iron cell cannot be determined by the density of the electrolyte, which does not change. Neither is the cell voltage or the amount of gassing a reliable guide. The only practicable method is to measure the output and input in ampere-hours, either by noting the rate in amperes and the time or by means of an ampere-hour meter. The manufacturers recommend a charge of 7 hours at normal rate after a discharge of 5 hours at the same rate, which is equivalent to 40 per cent. overcharge, in ampere-hours. The cell temperature should not be allowed to exceed 120° F.

The method of operation best adapted to the nickel-iron cell is that in which partial, or boosting, charges are given in the intervals between partial discharges. Boosting charges are particularly advantageous where the rate of discharge is sufficiently high to produce excessive polarization drop. The boosting charge quickly restores the cell voltage to normal, where otherwise it would remain abnormally low.

69. Changing Electrolyte.—The electrolyte in nickeliron cells gradually deteriorates, owing to the absorption of carbonic-acid gas from the air. Deterioration, however, cannot be absolutely prevented, and, although this gas does not permanently injure the plates, it reduces the capacity of the cells temporarily. About once in 6 months the electrolyte should be completely renewed.

Water that is to be used for filling the cells must be protected from exposure to the air for any considerable length of time, because water absorbs carbon dioxide (carbonic-acid gas) from the air. The local water supply, or even rainwater, which is very nearly pure, cannot safely be used for filling; distilled water protected from exposure to the air is generally necessary.

70. Special Precautions.—The containers of nickel-iron cells, being of metal, must be carefully insulated from each other and must be kept clean. The wooden crates in which the cells are supported, as well as the sides and floor of the battery compartment, must be kept clean and dry for the same reason. If the insulation between cells becomes defective from any cause, a small leakage of current will, by electrolytic action, puncture the steel containers.

The nickel-iron cell is gassing more or less at all times, whether charging, discharging, or standing on open circuit. These gases (oxygen and hydrogen) produce an explosive mixture. Care must therefore be taken to guard against bringing an exposed flame or producing an electric spark in the vicinity of the cells, unless the ventilation is very thorough.

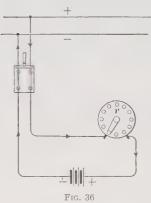
71. Repairs.—The covers of nickel-iron cells are welded in place after the cells are assembled. The plates cannot therefore be removed from the containers, and whenever repairs are required it is necessary to return the cells to the factory for this purpose.

STORAGE-BATTERY CONTROL AND CON-TROLLING APPARATUS

CONTROL OF CHARGE

72. The charging current of a storage battery can be controlled by means of a rheostat, by varying the voltage of the source of charging electromotive force, or by means of a booster.

73. Charging Through Resistance.—A charging rheostat is connected as at r, Fig. 36, where the voltage of the



charging source is greater than that required for the number of cells in series. In such cases, the voltage of the charging source should be approximately equal to the final voltage of the battery at the end of charge; the rheostat serves to reduce this voltage to that required at the beginning of charge, and the resistance is gradually cut out as the charge proceeds.

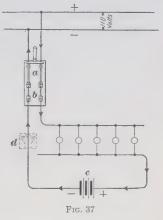
A few small cells can be conveniently charged from a lighting

circuit through lamp resistance. The current consumption of the lamps will then determine the charging current. Fig. 37 shows a method of connecting a battery to charge from a 110-volt circuit through five 110-volt, 16-candlepower, $\frac{1}{2}$ -ampere lamps connected in parallel, the charging current being practically $5 \times \frac{1}{2} = 2\frac{1}{2}$ amperes. The charging current passes through the switch a, the fuses b, the lamps, the battery c, and the ammeter d, if one is used. The lamps may be connected in either lead to the battery.

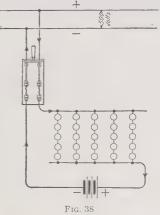
Fig. 38 shows a battery connected to charge from a 500-volt circuit through five series of lamps, each series consisting of five 110-volt, $\frac{1}{2}$ -ampere lamps connected in series. In this

case, the charging current will be a little less than $2\frac{1}{2}$ amperes, because 550 volts is required to send $\frac{1}{2}$ ampere through a series of five 110-volt, 16-candlepower carbon lamps.

This method of varying the charging current by varying the number of lamps, or series of lamps, in parallel is practicable only where the voltage of the cells is insignificant compared to that of the circuit. If, in the arrangement shown in Fig. 37, there are 25 cells in series, having a voltage between 55 and 65 while



charging, the voltage across the lamps will be between 55 and 45, or about half the normal lamp voltage. Only half the normal amount of current will then be transmitted through the lamps, provided their resistance remains constant. But

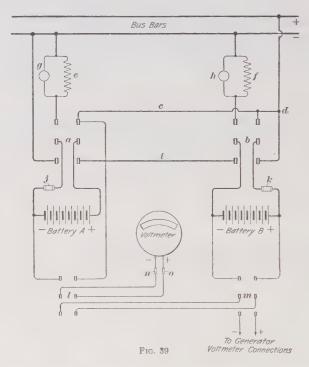


the resistance of a carbon-filament lamp increases as the amount of current through it decreases, while the resistance of a tungsten filament decreases as the current is reduced, and allowance must be made for this. The charging current is best determined by connecting an ammeter in circuit.

74. In many small plants for isolated lighting, the battery is divided into halves, which are charged in parallel through fixed

resistances and connected in series for discharge. Switchboard connections for such a system are shown in Fig. 39. The generator (not shown) is connected to the bus-bars through

a switch and fuses. With the double-pole, double-throw battery switches a and b in the upper positions, the batteries are, through the wire c, connected in parallel across the bus-bars. The main charging current then passes from the positive bus-bar, dividing at d, through the batteries and the fixed resistances e and f. Small portions of the charging current also pass through the pilot lamps g and h, which, by their



degree of brilliancy, serve to show roughly the state of charge of the batteries, becoming dimmer as the charge progresses. With the battery switches in the lower positions, the batteries are, through the wire i, connected in series between the busbars. The fuses j and k protect the batteries from excessive current during both charge and discharge. The double-pole, double-throw voltmeter switches are shown at l and m. With the switch l in its upper position, the voltmeter indicates the

voltage between the terminals of battery A, during charge; with switch l in its lower position and switch m in its upper position, the voltmeter shows the voltage across battery B during either charge or discharge; with each voltmeter switch in its lower position, the voltage of the generator is indicated. The voltmeter is protected by fuses n and o.

This system avoids the necessity of installing a generator of specially high voltage, and the generator can always be operated at normal lamp voltage, even when charging the battery, but the current required for charging the entire battery is twice the charging rate of the cells.

75. Charging by Raising Generator Voltage.—In some cases, especially in small isolated plants for residence lighting, the battery is charged by raising the generator voltage at a time when no lights are required, and the high voltage is not objectionable. If a few lights should be required during such a charge, the voltage can be reduced for these by a rheostat or, preferably, by counter-electromotive-force cells (described in Art. 85) connected in opposition to the main battery.

Connections for this system of charging are shown in Fig. 40. If no lighted lamps are required while charging, the switch a is opened and the double-pole, double-throw switch b is closed to the left, connecting the main battery directly across the terminals of the generator c. If lamps are to be used while charging, the switch a is left closed and the switch b is thrown to the left. The generator is again connected directly across the battery: but the voltage of the counter-electromotiveforce cells opposes the voltages of the generator and the main battery, and the voltage of the generator can be lowered by means of the field rheostat e to a value low enough for the proper operation of the lamps. With the battery switch a closed and the generator switch b open, the bus-bars receive the external voltage of the main battery minus the counter voltage of the cells d and the resistance drop in them; also, the cells d then receive a charging current. The counter voltage of the cells d and the drop in them can be varied by moving the switch blade f, which alters the number of counterelectromotive-force cells in circuit. An ammeter g indicates the current output of the generator; an ammeter h indicates the charging or discharging current, as the case may be, of the battery.

The connections of the voltmeter i are not shown completed in Fig. 40, but the wiring is actually so arranged that, by means of a voltmeter plug arranged as shown at i, voltmeter readings can be taken as follows: 1+ and 1-, generator voltage; 2+ and 2-, bus-bar voltage; 3+ and 3-, main

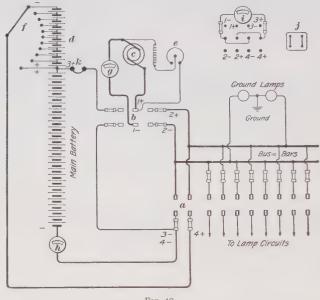


Fig. 40

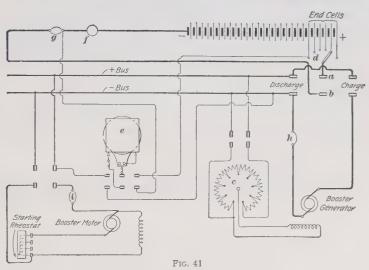
battery voltage; 4+ and 4-, main battery voltage less counterelectromotive-force-cell voltage—all as indicated by the numerals in the illustration.

The various circuits of Fig. 40 are protected from overload by fuses. An automatic underload switch k prevents the charging current to the main battery from falling below a certain predetermined value.

The ground lamps serve to indicate a ground on either side of the system. Ordinarily, both lamps burn dimly, but with

equal brilliancy. If a ground occur on either bus-bar or on the conductors connected with it, the lamp connected to that bus-bar will be extinguished and the other lamp will burn at full brilliancy.

76. Charging Through Booster.—In larger installations, the battery is usually charged by means of a booster, which is an auxiliary generator whose voltage is added to that of the main generator or other source of current in order to provide the additional voltage required for charging the battery.



This method of charging is preferable to either of the other two methods for batteries of large capacity, inasmuch as it obviates the rheostatic losses and permits current for lighting or other purposes to be taken directly from the main dynamo at normal voltage while the battery is being charged through the booster. This booster is usually direct-connected to a motor but may be belt-driven if convenient.

The system of connections for charging through a booster is shown in Fig. 41. The generator (not shown) is connected, through a switch, to the bus-bars. The battery is connected to the middle posts a and b of a double-pole, double-throw

switch. When this switch is closed at the right, charging current passes from the positive bus-bar, through the battery, through the booster generator, to the negative bus-bar. In the opposite, or discharge, position of the double-throw switch, the battery is connected directly across the bus-bars.

The field excitation of a booster must be under such control that the booster voltage can be varied from zero to the maximum. The booster cannot be self-excited, as the voltage would become unstable at low field saturation. The field is therefore separately excited from the main bus, a three-terminal rheostat c, Fig. 41, being used. This rheostat is connected directly across the circuit, and has a few high-resistance steps at one end to reduce the continuous flow of current. One field terminal is connected to one side of the circuit and to one terminal of the rheostat winding, and the other terminal is connected to the rheostat arm, so that when this arm is at one extreme of its travel, the field winding is connected across full bus voltage, while when the arm is at the other extreme, the field winding is short-circuited, and the excitation is then reduced to zero.

The battery of Fig. 41 has five end cells that can be cut into or out of circuit, one at a time, by means of the end-cell switch d. The use of end cells is described under the heading Control of Discharge.

Fig. 41 also shows a recording voltmeter e that can be connected, by means of a double-pole, double-throw switch across either the main battery (exclusive of the end cells) or the bus-bars. This is standard practice in battery installations of considerable size.

An ammeter f indicates the current output or input of the battery, and a circuit-breaker g protects it from overload. An automatic underload switch h prevents the charging current from falling below a predetermined value. A circuit-breaker i protects the booster motor from overload.

CONTROL OF DISCHARGE

METHODS OF CONTROL

77. In many small plants where the discharge rate is low, no control of the discharge voltage is provided, the variation from the beginning to the end of discharge not being objectionable. Where control of the discharge voltage is required, three different methods are used: by means of end cells, by means of counter-electromotive-force cells, and by means of a booster.

END-CELL CONTROL

78. Principle of End-Cell Control.—End-cell control consists in the variation of the discharge voltage by cutting in or out one or more cells at one end of a series. The method is illustrated in its simplest form in Fig. 42, in which A is

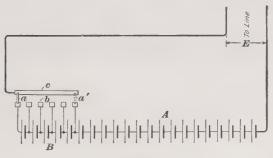


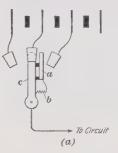
Fig. 42

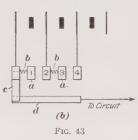
the main battery and B a number of cells from each of which connection is made to the contacts b of an end-cell switch. A contact piece is arranged so that it can be moved to any of the contacts b from position a to a' by means of a suitable mechanism, and the number of cells in use thereby varied. When the battery has been fully charged, the end cells are cut out of circuit and the contact occupies the position a'. As the voltage runs down, the contact is moved to the left

and fresh cells are cut in, thus maintaining the voltage E at the desired amount.

End-cell control is adopted where changes of load take place slowly and there is ample time for hand control, as, for example, in electric-lighting service. The end-cell switch can be operated directly by hand for smaller installations, but is generally motor driven with remote control for larger installations.

79. Hand-Operated End-Cell Switches.—In order to avoid opening the circuit when the arm, or brush, of an end-





cell switch passes from point to point, and at the same time prevent short-circuiting the cell or cells connected across adjacent points, auxiliary contacts a, Fig. 43 (a) and (b), are provided; these are connected through a suitable resistance b either to the traveling arm c or to the stationary contacts.

Hand-operated cell switches for 50 to 500 amperes, inclusive, are of the round, or dial, pattern, as shown in part in Fig. 43 (a). The auxiliary contact a is carried by the main arm c, from which the auxiliary arm is insulated, except through the resistance b. When the switch is turned either to the right or to the left, the stationary contacts are momentarily

bridged by the main arm and the auxiliary, so that the circuit is not opened; yet a short circuit of one cell is prevented by the resistance. This resistance is sometimes in the form of a coil wound around the shaft on which the arm is mounted. The switch is mounted on a switchboard and operated by a handle, not shown in the illustration. Current is taken from the arm by a sliding contact on the back of the board.

Hand-operated switches of 500 to 1,000 amperes are of the horizontal type shown in Fig. 43 (b). The continuous contact

rail d is connected to any one of the series of points above by the traveling brush c, the motion of which is effected by a rack and pinion, the rack being stationary and the pinion carried by the handle (not shown), which moves with the brush. Adjacent contact points, as 1 and 2 or 2 and 3, are close enough together to be bridged by the traveling arm; but alternate points, as 2 and 4, both connected directly to the battery cannot be bridged by the arm. This arrangement permits movement of the arm without opening the circuit or short-circuiting the cells.

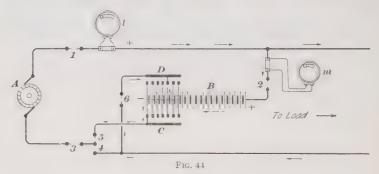
80. Motor-Driven Cell Switches.—Motor-driven cell switches are of the horizontal type, similar to Fig. 43 (b), consisting of a row of contact points with auxiliary contacts between and a horizontal conducting rail, the traveling arm usually being driven by a long, horizontal screw rotated by an electric motor. The auxiliary contacts, which prevent short-circuiting the intervening cells while the arm, or brush, is passing from one contact point to the next, consist of carbon blocks. The brushes usually also carry carbon trailers on each side.

In one type of motor-driven end-cell switches, the motor is controlled by means of two electromagnets. Each magnet, when excited, operates a switch to connect the motor armature across the bus-bars—one switch for one direction of motor rotation and contact-arm travel, and the other for the opposite direction. The magnets are selectively excited by means of a single-pole, double-throw control switch at the switchboard, so that the operator can start the motor in either direction at will. A cam geared to the motor and designed to make one revolution while the brush is traveling from one point to the next engages the active switch as soon as it is closed by the electromagnet, preventing it from opening on interruption of the exciting current of the magnet until the brush comes in full contact with the next switch point. Thus, the operator cannot stop the brush between two points of the switch. At each end of the cell switch is a limit switch, mechanically opened by the brush, to interrupt the exciting circuit of one of the electromagnets and prevent further travel of the brush in that direction.

Another arrangement has on the switchboard an illuminated dial carrying a series of numbers representing the several end cells. This dial can be set by the operator at the point corresponding to that to which the cell-switch brush shall travel, and the brush will thereupon be driven by the motor to the desired point and stop there automatically without further attention on the part of the operator.

In another make of end-cell switch the traveling brush is moved by a complicated arrangement of bars and pawls.

81. Control by Two Cell Switches.—When a battery whose discharge voltage is controlled by end cells is charged



by raising the dynamo voltage, a second end-cell switch is sometimes added to provide voltage for lamps that may be required during the charging period, the voltage of the dynamo being too high for the lights. The connections for this arrangement are shown in Fig. 44. Switches 1, 2, and 3 are closed and the double-throw switch 4, 5 is in the upper position; the battery is charging, and the path of the charging current is represented by the dotted arrows. At the same time, the generator A is furnishing current to the line, as indicated by the full-line arrows. With the end-cell switch D in the position shown, the pressure between the lines outgoing to the load is that of the main battery B plus that of two end cells, while, owing to the position of switch C, the pressure of the generator

must be high enough to charge the entire battery, including the end cells. Ammeters *l* and *m* measure the generator current and battery current, respectively.

82. Number of End Cells in Series.—The number of end cells in series is the difference between the total number of cells in series in the entire battery and the minimum number permissible in the main battery. The total number of cells in series, including end cells, is determined by dividing the bus voltage to be maintained by the final voltage per cell at the end of discharge (Art. 31). In this connection, it may be noted that the bus voltage can frequently be allowed to drop below normal at the end of discharge, especially where the chances of a complete discharge at maximum rate are quite remote; this is standard practice in designing large battery installations for standby service in central lighting stations.

If the battery is to be disconnected from the bus while charging, the number of cells in series in the main battery may be found by dividing the lowest allowable bus voltage by the floating voltage (see Art. 30). If the battery must be connected to the bus while charging, the number of cells in the main battery may be found by dividing the bus voltage by the maximum cell voltage at the end of charge (Art. 32).

For example, if a bus voltage of 115 is to be maintained, the total number of cells in series, including end cells, must be $115 \div 1.75 = 66$. If the battery is to be disconnected from the bus while charging, the number of cells in series in the main battery will be $115 \div 2.1 = 55$, assuming a floating voltage of 2.1 per cell. If the battery must be connected to the bus while charging, the main battery will contain $115 \div 2.5 = 46$ cells in series, assuming a maximum cell voltage of 2.5 at the end of charge. In the first case, therefore, the number of end cells in series will be 66-55=11, and in the second case, 66-46=20.

83. Grouping of End Cells.—In general, end cells are connected singly to the cell switch; that is, one cell across each pair of adjacent points. In special cases, as in batteries

for emergency standby service, the extreme cells are connected to the cell switch in groups of two or three to a point. This reduces the cost of the cell switch and the end-cell copper, and also reduces the time required to cut in the end cells in a high-rate emergency discharge.

84. Charging End Cells.—Since the end cells of a battery are cut in step by step during the discharge, some are not fully discharged and require less recharging than others. The charge is started with all cells in circuit, and the end cells are cut out step by step in the reverse order, as they become fully charged.

COUNTER-ELECTROMOTIVE-FORCE CELLS

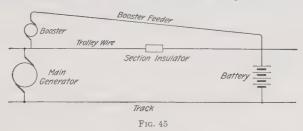
85. In small installations, for residence lighting, etc., counter-electromotive-force cells are used instead of end cells for controlling the discharge voltage. The plates in these cells are merely grids without active material, and therefore have no capacity except that due to a thin coating of active material that gradually forms on the surface of the grids with use. The voltage of counter-electromotive-force cells opposes the discharge current, and is deducted from the voltage of the battery at such times as the beginning of discharge and during charge. Counter-electromotive-force cells do not always carry the charging current (see Fig. 40). As the battery voltage drops during discharge, the counter-electromotive-force cells are cut out of circuit step by step by means of an end-cell switch.

Counter-electromotive-force cells are preferable to a rheostat for this purpose, because the voltage drop in them is nearly constant, regardless of the current, whereas the drop of voltage in a rheostat is directly proportional to the current it carries, thus requiring a change of adjustment with change of load.

BOOSTER CONTROL

86. Line Batteries.—Storage batteries are frequently employed to smooth out automatically the fluctuations of load or voltage that are too rapid for hand control. The

simplest form of regulating battery is a *line battery* connected directly across the circuit at a place sufficiently remote from the source of power to introduce considerable line drop. If the load is variable, the voltage at the battery site will be variable, and this will cause the battery to charge and discharge. The number of cells in series is so chosen that the battery floats when the line voltage is at its average value. An increase of load then causes the battery to discharge, and a decrease causes it to charge. For example, if the average, or floating, voltage at the point of installation is 450, 214 cells in series are installed. If the 1-hour rate of the battery is 200 amperes, and the internal resistance drop at the 1-hour rate, including some polarization, is about 8 per cent. of the floating voltage, or 36 volts, then the equivalent internal



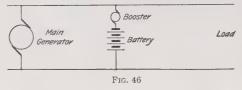
resistance of the battery is $36 \div 200$, or .18 ohm. If the resistance of the line conductors is 1 ohm, the fluctuations of load divides between the battery and the conductors in the ratio of 1 to 1.18; that is, the battery takes $1 \div 1.18$, or about 85 per cent., of the fluctuations.

If the average voltage at the point where the battery is to be installed is too low for satisfactory operation, this voltage can be increased by the use of a booster feeder; a separate feeder extends from the power house to the battery station, as shown in Fig. 45, which represents, roughly, a railway system. A shunt-wound booster in series with the feeder at the power house raises the voltage.

87. Function of the Booster.—A line pattery performs the dual function of reducing the fluctuations of voltage at the point where it is installed and of relieving the system of

a part of the load fluctuations in its vicinity. Similarly, a battery connected across the line at the source of power will regulate more or less if the source has a drooping characteristic; that is, if its voltage falls with increase of load and rises with decrease, as does that of a shunt-wound or a differentially wound generator. If, however, the voltage of the circuit is constant at the battery site, the battery cannot charge or discharge without some controlling apparatus to compel it to do so. The regulating, or automatic, booster is employed to control both the charge and discharge of a battery when the fluctuations of load are too rapid for hand control, as in the case of an electric-railway load or intermittent power service.

Two methods of connecting such a booster are used, giving rise to two types of booster, namely, the series regulating booster, and the con-



88. The series regulating booster, or reversible booster, as

stant-current booster.

it is sometimes called, is a generator run at constant speed and connected in series between the battery and the main bus or circuit to which both the main generators and the load circuits or feeders are connected, as shown in Fig. 46. This booster, therefore, carries the total battery current, and the direction of the current in the booster field determines the direction of the booster voltage. When the battery is neither charging nor discharging, its voltage is usually approximately the same as that of the bus, and the booster generates no voltage. When the battery is discharging, its voltage drops, and the booster voltage is added to that of the battery to compensate for the drop. When the battery is charging, its voltage rises, and the booster voltage is added to that of the line. The voltage of the booster and the current in its armature thus reverse in direction at the same time or nearly so. This scheme is used in electric-railway regulating batteries.

89. The constant-current booster is connected between the generator and the battery, with the fluctuating load directly across the battery terminals, as shown in Fig. 47. A unidirectional and substantially constant current is transmitted from the generator through the booster armature to the circuit to which the battery is connected. When the demand for current on this circuit exceeds this amount, the battery discharges to supply the deficiency. When the demand is less, the surplus charges the battery. The booster voltage varies in accordance with the changes of battery voltage with charge and discharge. This system is used principally to control the fluctuations of loads of electric elevators in office buildings, etc.

With the series regulating booster, the entire load is taken from one circuit, and the voltage impressed on this circuit

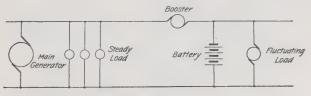


Fig. 47

is substantially constant, being that of the main bus to which the main generator is connected; with the constant-current booster, the lamp circuit and power circuit are separated, and the voltage impressed on the latter is variable, being that of the battery. The constant-current system is employed, therefore, only when the transmission distance is short and the drop of voltage under heavy load is not objectionable. The principal advantage of the constant-current system is the reduction in the size and the cost of the booster made possible when the average load is much smaller than the maximum load.

90. Carbon Regulator.—A device frequently employed for controlling automatically the voltage of either main type of booster, to compel the battery to charge and discharge with fluctuations of load, is the carbon regulator, shown in perspective in Fig. 48 and diagrammatically in Fig. 49. The

regulator consists of two sets a and b of carbon disks so arranged on opposite sides of the fulcrum of a lever c that force applied to one end of the lever will compress one set and relieve the pressure on the other, thus producing a wide variation of contact resistance between the disks. The carbon piles are connected in series across the battery terminals d and e, Fig. 49, and the field winding of the booster exciter is connected between the middle point f of the battery and a point between the two sets of carbon piles. The pressure exerted on the carbon

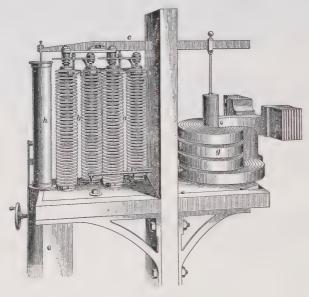


Fig. 48

piles is controlled by an adjustable spring at one end of the lever and a solenoid g, Figs. 48 and 49, at the other. The solenoid is connected in the main generator circuit and carries the total output of all of the generators.

When the output of the main generator is normal, the pull of the solenoid is balanced by that of the spring, the pressures on the two sets of carbon piles are equal, and their resistances are equal. There is then no current in the exciter field winding, the booster voltage is zero, and the battery

floats on the line, neither charging nor discharging. A small portion of any increase in load is supplied by the main generators, increasing the pull of the solenoid and thereby compressing one set a of carbon piles and relieving the pressure on the other set b. The equality of the resistances of the two sets of carbon piles is thus destroyed, and the exciter field winding receives current through the path f-a-e, Fig. 49, in such a direction that the resulting booster voltage aids the battery voltage. The battery then discharges and relieves the generators of all the increase in load, except the small part necessary to actuate the regulator. Upon decrease of load below normal, the regulator spring overcomes the pull of the solenoid,

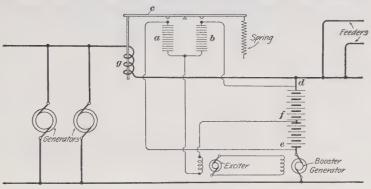


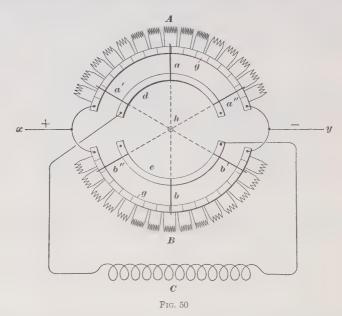
Fig. 49

and the resulting compression on set b of carbon disks sends current through the exciter field winding by the path d-b-f. The booster voltage is now built up in such a direction as to oppose the battery voltage, causing the battery to be charged. A substantially constant load on the generators is thus maintained.

In some installations, the carbon piles are connected across only a section of the battery; in others, the exciter is not used, and the regulating current passes directly through the booster field winding. In every case, however, the general principle of operation is the same.

In Fig. 48, the regulating spring is concealed in the cylindrical casing h. Adjustment of the tension of this spring is obtained by means of the hand wheel.

91. Reversing Rheostat for Booster Field.—Fig. 50 illustrates a special type of field rheostat used when the voltage of the booster is to be reversed and controlled by gradual steps in either direction. Equal resistances A and B are split into a number of sections and connected to the insulated segments g, as shown; d and e are stationary contact arcs, and a lever pivoted at h carries moving contacts a and b that bridge between the segments and the contact arcs. Terminals x and y are connected either to the bus-bars or to the



battery terminals, and the arcs d and e are connected to the field winding C of the booster. The scheme of connections is the same as a Wheatstone bridge with the galvanometer replaced by the field C. When the lever is in the vertical position ab, there is no difference of potential between the field terminals, and the field is unexcited. As the lever is moved over toward the position a''b'', the pressure across the field terminals is gradually increased until the extreme position of the lever is reached, and e is connected directly

to the + terminal and d to the - terminal. A movement of the lever in the reverse direction; that is, from the vertical position toward a'b', gradually increases the pressure across the field but in the reverse direction. This rheostat therefore allows the booster to be used as an aid either in charging or discharging, and also allows close regulation of the charging and discharging current. In order to make the waste of energy small, the central sections of the rheostat have a high resistance.

92. Compound Booster.—The voltage of a compound booster is controlled by a series winding and a separately

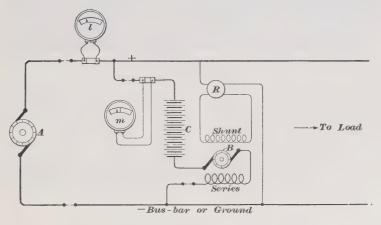


Fig. 51

excited shunt winding, the booster armature B, Fig. 51, and its series winding being connected in series between the battery and the line. The series winding is designed to give a booster voltage in the same direction as the current, and sufficient in value, for any given current, to compensate for the ohmic drop in battery voltage due to that current. The shunt-field excitation is adjusted by hand to compensate for those changes of battery voltage which are due to polarization or for changes in bus voltage. Since the direction of current in the shunt field may at times have to be reversed, a reversing field rheostat R is used for the shunt-field control. Ammeters l and m indicate the outputs of the generator A and battery C, respectively.

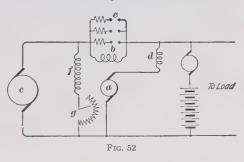
Inasmuch as this type of booster depends for automatic control on the charge or discharge of the battery to excite its series field, it cannot act as the original cause for such charge or discharge. This combination must therefore operate on a system having a drooping characteristic; that is, the line voltage must drop with increase of load. This variation of line voltage will start the battery charge and discharge, the booster acting to augment the action of the battery and maintain a more nearly constant voltage. The rheostat R is so adjusted that when the generator is delivering its normal load at normal voltage, the voltage of the booster plus that of the battery just equals the voltage of the generator; under these conditions there will be neither a charging nor a discharging current. If the load on the line increases, the voltage of the generator tends to drop on account of the increased load momentarily thrown on it. This allows the battery to discharge, and the discharging current through the series coils of the booster raises the combined electromotive force of the battery and booster, thus making the battery at once take such a share of the load that the electromotive force across the lines is restored to normal. On the other hand, a decrease in the external load below the normal tends to make the generator voltage increase. The battery then charges, and the charging current through the series-coils of the booster opposes the shunt coils, thus lowering the booster voltage and allowing the charging current to increase until the generator voltage comes down to normal. In actual working, the voltage of the system changes very slightly, as any tendency to change is checked by the operation of the battery and its booster.

This type of booster is sometimes used with a large line battery designed for sustained high-load discharge, as well as for regulating momentary fluctuations, especially where the variations of line voltage are not of sufficient range fully to utilize the battery capacity.

93. Counter - Electromotive - Force Booster. — The counter-electromotive-force booster requires an exciter a, Fig. 52, with a field b connected in series with the main generator c

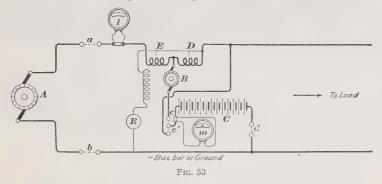
The exciter armature, in series with the booster field d, is connected across the bus-bars. Under average load conditions, the exciter develops a voltage equal to the bus voltage; then no current passes through the booster field winding, the booster voltage is zero, and the battery floats on the line.

Any fluctuation of load changes the exciter field flux by changing the current in the series field winding, thus changing the voltage of the exciter to a value above or below that of the bus; the booster



field winding then receives current in one direction or the other, causing the battery to either charge or discharge, depending on whether the load has decreased or increased.

To adjust the exciter voltage for different average loads, several shunts e, Fig. 52, are provided for connection across



the exciter field. Sometimes the adjustment is obtained by means of a shunt field winding f and a rheostat g.

94. Differential Booster.—The differential booster has two series field windings so connected that one E, Fig. 53, carries the current of the generator A, while the other D carries the total load current including the discharge current of the

battery C. The booster armature B is in series with the battery. The two series coils are designed to produce a booster voltage to cause the battery to discharge; the shunt field winding is designed to oppose the series windings. When the demand on the load circuit is equal to the desired average generator load, the shunt field is adjusted by means of a rheostat R to neutralize the series fields; the booster voltage is then zero and the battery neither charges nor discharges. Any increase of load, passing through the outside field D, produces a voltage suitable to make the battery discharge and relieve the generator of the increase. If the shunt-field adjustment is not quite perfect, part of the increase of load, falling on the generator, produces an increase of current in the inside series winding E, which then assists the outside winding D. If the load falls below normal, the magnetizing effect of the shunt field predominates, thus making the booster generate an electromotive force in the reverse direction and allowing the battery to charge. The load on the generator is therefore kept practically constant in spite of the fluctuations of the load delivered from the station.

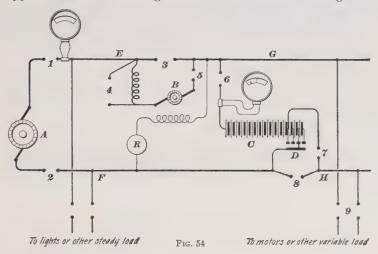
Main generator switches are indicated at a and b, Fig. 53, and battery switches at c and d. With switch d closed and the single-pole, double-throw switch in the position c, the booster is in circuit; with this latter switch in position c', the booster is out of circuit. Ammeters l and m measure the generator and battery currents, respectively.

Because of the cost of the heavy series windings and cable connections, no new installations of differential boosters are being made, though some of the old installations are still in operation.

95. Series-Wound Constant-Current Booster.—A method of connections for the automatic control of the voltage of a constant-current booster is shown in Fig. 54.

The generator A supplies current to the bus-bars E and F to which the steady load is connected. The fluctuating load is connected to bus-bars G and H, and the booster armature B and series-field are connected in series between E and G. The

fluctuating load current does not pass through any of the booster windings as in the case of the compound and differential boosters; the booster carries only the average current supplied by the generator to the power system. An end-cell switch D is usually provided so that the battery can be operated on the lighting load only, the cells being cut in as the voltage drops. The booster is provided with a shunt winding, which sets up an electromotive force in the armature in a direction such as to aid the generator electromotive force. The series coils oppose the shunt coils and set up an electromotive force opposed to that of the generator. The current through the



booster is not reversed, because the only current through it is that supplied by the generator. Under ordinary operating conditions, switches $1,\,2,\,5,\,6$, and 7 are closed. Then, in case a heavy load comes on the power circuits, the tendency is for a heavy current to be delivered by the generator through the booster. The voltage across the terminals of the battery is equal to the generator voltage plus that of the booster; any increase of current in the series field causes a lowering of the booster electromotive force. The result is that the pressure across the battery terminals decreases, thus causing the battery to discharge and supply the extra demand

for current. Conversely, a decrease in the fluctuating load causes the battery to charge. The generator therefore delivers an approximately constant current; the irregularities due to the heavily fluctuating motor load are so smoothed out that the pressure supplied to the lamps is practically uniform.

If both loads must be operated directly from the generator, the battery and booster can be cut out as follows: The booster is shut down and switch 3 closed. Switch 3 cannot be closed while the booster is generating, because armature B would be short-circuited. Switch 5 is then opened and the booster thereby cut out of service. By opening switches 6 and 7 and closing switch 8, the battery is cut out and the generator is connected directly with the load circuit. Switch 7 must be opened before 8 is closed; otherwise, the end cells will be short-circuited. If it is desired to cut off the fluctuating load and run the lights from the battery alone, switches 8 and 9 are opened and switch 6 is closed. This cuts off the fluctuating load and places the battery, with its end cells, in parallel with the generator, it being understood that the booster is now out of service. By opening switches 1 and 2, the generator is cut off and the whole lighting load is carried by the battery, the regulation being effected by means of the end-cell switch. When the battery is to be given a full charge, the booster can be operated as a plain shunt generator by cutting out the series coils by means of the short-circuiting switch 4.

This type of booster was formerly used for the regulation of fluctuating elevator loads in office buildings; some are yet in operation. The series-wound constant-current booster is still installed occasionally where the average load is small and the cost of the series winding is not excessive.











